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BENCH SCALE EVALUATION OF ANTHRACITE THERMAL COAL MIXTURE FOR A PULVERIZED FIRING SYSTEM

By
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1. SUMMARY

This Research Contract investigates combustion of individual coals, and coal mixtures by three bench scale techniques:

(1) Thermogravimetric Analysis (TGA)
(2) Differential Scanning Calorimetry (DSC)
(3) Laboratory Scale Entrained Flow Combustor (EFC).

All these methods are useful in assessing the relative ease of ignition of individual coal samples. "Ignition" temperatures determined by these techniques can be correlated with one another. TGA's volatile release profile provides basic information on the amount of "reactive" components present in a coal sample; and carbon burnout from EFC gives insight into the reactivity of the char component.

Combustion evaluations of coal mixtures by TGA and EFC, however, only give inconclusive results. TGA data show that a common combustion temperature range assists in combustion interaction; but the flammability temperatures from EFC indicate that this is not a deciding factor. In the initial phase of combustion, interaction of reactive components lowers the "ignition" temperature of the inert component at the expense of the more reactive thermal coals.

The data on carbon burnout of coal mixtures also suggest different combustion behaviours. Anthracite from conventional grind appears to inhibit the combustion of other thermal coals, but when the anthracite is ground to micronized size, the coal particles appear to be combusted individually in a coal mixture. Interaction in the combustion of char components may be quite different from those in the initial phase of ignition.

Due to the inherent differences in the environments between bench scale techniques and an operating pulverized firing system, the evaluation of combustion characteristics of coal mixtures should be carried out in a larger scale burn test. A larger scale burn test would be useful in corroborating the combustion characteristics determined in this contract and confirming the flame stability of coal mixtures.

2. INTRODUCTION

This report describes work performed during 1986-87 on D.S.S. Contract 06SQ.23440-6-9058, "Bench Scale Evaluation of Anthracite Thermal Coal Mixtures For a Pulverized Firing System".

The prime objective of this project was to investigate the interaction between anthracite coal and a more reactive thermal coal during combustion.

Thermogravimetric Analysis (TGA), Differential Scanning Calorimetry (DSC), and a Bench Scale Entrained Flow Combustor (EFC) were utilized to evaluate combustion characteristics.

This research contract consists of three tasks as outlined in the work statement in Appendix 1. The specific objectives of this research program are:

1. To analyze the coal samples used in this research program (Task 1).

2. To determine the combustion temperatures of individual coals and coal mixtures by thermogravimetric analysis (TGA) (Task 2).

3. To obtain supporting data on combustion temperatures of the individual coals by differential scanning calorimetry (DSC) (Task 2).

4. To determine the flammability temperatures and carbon burnout of individual coals and coal mixtures in a Bench Scale Entrained Flow Combustor (EFC) (Task 2).

5. To correlate the combustion temperatures determined by TGA, DSC, and EFC studies. (Task 2).

6. To assess the experimental results and prepare a Final Report (Task 3).

The results of this Research Contract are described in detail in this final report.

3. INSTRUMENTATION & EXPERIMENTAL

3.1 Instrumentation

3.1.1 TGA & DSC

Thermogravimetric Analysis (TGA) and Differential Scanning Calorimetry (DSC) were carried out using an omnitherm 25TG950 thermogravimetric module and omnitherm 910 DSC module, respectively. These modules were supervised by a Dupont 1090 Thermal Analyzer based system. The 1090 base unit performs module programming and control as well as data acquisition and analysis, using a Dupont 1091 dual disk memory unit.

3.1.2 Entrained Flow Combustor (Drop Tube Combustor)

The entrained flow combustor at the Alberta Research Council (ARC) consists of a solids feed system, an isothermal high temperature reactor (500 to 1100°C) and a solid collection filter (Figure 1). The solid fuel is fed to the reactor through a fluidized bed feeder. A narrow size range (usually -140 to +170 mesh) is fed at 0.06 - 0.1 g/min with 0.5 l/min of transport air to the reactor. A narrow size range of particles is used to aid in the interpretation of combustion mechanisms from the analysis of physical changes of the particle during reaction. The reactor consists of a 25.4 mm stainless steel tube with a 12.5 mm O.D. by 3.2 mm I.D. water cooled injector at the top and a 19.0 mm O.D. by 6.4 mm I.D. collector at the bottom. The coal and transport air enter the reactor at room temperature through the injector, and the secondary air, preheated to reaction temperature, enters the reactor through the annulus between the injector and outside reactor tube.

The flow rate of secondary air is adjusted in the range of 1.5 - 3.5 l/min to obtain the desired reactor residence time. This flow provides 300 - 600% excess air for the combustion reaction and ensures that the combustion reaction is not limited by oxygen depletion. The large amount of excess air also limits the rise in gas temperature from the combustion process.

The particles are collected in a water cooled probe which effectively

quenches the particles, allowing the residence time of the particles in the gas zone to be determined accurately. A Balston filter connected to the end of the collector traps all of the residue. The capability for measuring the combustion gas composition with a Microsensor gas chromatograph is included in the design.

In a typical test, the furnace is brought to operating temperature and adjusted to obtain an isothermal gas temperature in the reactor at the selected gas flow rate. The isothermal gas temperature is measured using suction pyrometers, consisting of an unshielded one-sixteenth inch K-type thermocouple enclosed in a one-eighth inch stainless steel tube. There are three suction pyrometers located along the length of the isothermal zone. Once isothermal conditions are attained, char is injected into the primary gas flow and collected in the filter. The quantity of unburnt carbon is calculated and the solid samples are collected for analysis.

3.2 Experimental

3.2.1 TGA Experiments

- Volatile Release Profiles
  - Heating rate 5°C/min
  - Nitrogen Flowrate 40 ml/min
  - Sample wt: 25 - 30 mg

- Combustion Profiles
  - Heating rate 5°C/min
  - Air flowrate 40 ml/min
  - Sample wt: 30-40 mg

3.2.2 DSC Experiments

- Heating rate 5°C/min
- Air Flowrate 50 ml/min
- Sample wt: 3 - 10 mg

3.2.3 Entrained Flow Combustor (EFC)

Flammability Index. Using A sized fraction, 0.2 gms is injected into preheated oxygen through the EFC at a carefully controlled gas temperature. This temperature will be raised in 20°C increments until ignition is observed. The ignition temperature will be determined within ±5°C for each sample. The micronized sample is studied in a similar manner. Approximately 4 gms of sized sample will be required for each flammability index determination.

Combustion Tests. The sized and micronized samples are injected into a preheated gas stream at a temperature of 1000°C to 1100°C containing 5% or 21% oxygen in nitrogen. Particles will be extracted from the reactor at three residence times from 60 to 500 ms and analyzed for ash content to determine the rate of carbon burnout.

The residence time of particles in the heated zone will be controlled by a combination of gas flow rate and the distance between water cooled injection and collection probes. A mathematical model of the EFC is used to calculate particle residence time from the gas flow rates, reactor length, and temperature.

4. COAL QUALITY

A simulated clean coal from Gulf's Mt. Klappan property was used as the anthracite component. Coal samples from Goodrich and Luscar-Sterco's Coal Valley were supplied by the Energy Research Laboratories (ERL) of CANMET. An Obed sample and its beneficiated product, using the Gulf Beneficiation Process, were also studied in this research program.

All the samples used in this program were prepared to a conventional grind (250 µmxo) for analysis. Proximate and ultimate analyses of the samples from Mt. Klappan, Goodrich, and Coal Valley were carried out by Loring Laboratories Ltd. in Calgary. The results are shown in Table 1. All the samples used in this project were subsequently analyzed by Alberta Research Council prior to the entrained flow combustor experiments. The Obed sample used in this contract is also referred as Obed Mountain Coal in ARC's report. The analytical data from ARC are presented in Table 2. The identifications of individual coal samples used in this research program are listed below:

A1	...	Mt. Klappan Anthracite conventional grind (250 µmxo)
A2	...	Mt. Klappan Anthracite micronized grind (45 µmxo)
C	...	Coal Valley Bituminous
G	...	Goodrich Bituminous
O	...	Obed Bituminous
B1	...	Upgraded Obed

5. BENCH SCALE COMBUSTION EVALUATION OF ANTHRACITE THERMAL COAL MIXTURES

This section discusses the results of the main task of this research program. Combustion characteristics of individual coals and coal mixtures were evaluated by three techniques:

- Thermogravimetric Analysis (TGA)
- Differential Scanning Calorimetry (DSC)
- Bench Scale Entrained Flow Combustor (EFC).

In addition to the combustion evaluations, volatile release profiles by the TGA method were also obtained for background information.

5.1 Thermogravimetric Analysis (TGA)

5.1.1 Volatile Release Profile

Volatile release profiles determined by thermogravimetric method for individual coals are attached in Appendix 2. These profiles were obtained at a heating rate of 5°C/min, a nitrogen flow rate of 40 ml/min, using a sample weight of 25 - 30 mg.

The inert atmosphere used in volatile release profile determinations prevents the coal from oxidation and combustion. The loss of mass at various temperatures, except for those due to water removal, can be considered to be caused by thermal degradation of the coal samples. Therefore, the extent of mass is a direct indication of the "reactive" species present in a particular coal sample.

A review of the volatile release profiles in Appendix 2 shows that there are significant differences between bituminous coals and anthracite. Bituminous coals began to lose mass at a lower temperature and at a faster rate, resulting in a higher weight loss at various temperatures covered in this evaluation. The Beneficiated Product (B1) showed a slight increase in weight loss than its parent

coal (0). While the final mass loss at 900°C, which is the temperature at which volatile matter determination is carried out in ASTM specification, agrees well with the volatile matter content in all cases, the release of volatile matter at lower temperatures are more crucial in determining the combustion temperatures of coal. Table 3 summarizes the mass loss at various temperatures for all the samples of different grinds. The mass loss at 300 - 500°C range for bituminous coals are substantially higher than those from anthracites.

The effect of micronized grind on volatile release is also shown in Table 3 by comparing the results observed for samples A1 and A2. At all temperatures, the micronized grind (A2) shows a larger mass loss than the conventional grind (A1). The increased release of volatile matters tends to lower the combustion temperatures of the coal sample.

5.1.2 Combustion Profiles

All the combustion profiles in this project were determined under the same operating conditions: 5°C/min heating rate, 40 ml/min of air flow rate, using 30 - 40 mg of coal samples. These profiles are attached in Appendix 3.

Combustion profiles obtained by thermogravimetric method, covering a temperature range from ambient to 800°C, contain a great deal of complex information: water removal, oxidation, thermal degradation, and combustion. At elevated temperatures above 800°C, thermal decomposition of minerals resulting in a net gain or loss of mass is also registered.

Notation. The most difficult task in analyzing TGA combustion profiles is to identify the onset temperature because it is greatly complicated by the occurrences of mass losses due to water removal, oxidation, and volatile release. Since the prime objective of this program is to compare combustion on a common basis, a standard procedure was developed to determine the temperatures at various stages of combustion (1).

The symbols and their definitions used for coal combustion temperatures in this report are described below. A specimen thermogram showing all these temperatures is shown in Figure 2.

T_o Initial temperature of combustion. Defined as the last temperature at which the derivative curve crosses the base line.

T_{xo} Onset temperature of combustion. Obtained at the intersection of a tangent line drawn at the first point of inflection and the tangent line drawn at T_o, on the primary curve.

T_{25}, T_{50}, T_{75}
Temperature of 25%, 50%, and 75% combustion of carbonaceous material (dry ash free basis of coal).

T_{xc} Temperature of complete combustion. Obtained at the intersection of a tangent line drawn at the last point of inflection and the tangent line drawn at constant weight at elevated temperature, on the primary curve.

T_i Temperature of inflection point on the primary curve.

Based on the notation outlined above, a combustion profile can be broadly subdivided into areas of pre-combustion, combustion, and post-combustion. Post-combustion deals with the decomposition of minerals at elevated temperatures and is of little interest in this study. The precombustion stage covers the temperature range between ambient to T_{xo} which shows the net result of water evaporation, loss of "reactive" species, and oxidation. The combustion stage between T_{xo} and T_{xc} is discussed in the following section.

TGA Combustion. Between the temperature boundaries of T_{xo} and T_{xc}, the carbonaceous materials in coal are consumed to produce carbon dioxide, water and heat. Bituminous coals showed a higher rate of mass loss than anthracite, indicating that the carbon present in anthracite is more thermally stable (Appendix 3).

The combustion temperatures (T_{xo} to T_{xc}) of bituminous coals and the Mt. Klappan anthracite coal studied in this program are also quite different. Obed coal has a combustion temperature range between 352°C and 424°C, its beneficiated product between 360°C and 428°C. Coal Valley ranges from 381°C and 425°C, Goodrich from 418°C to 495°C, and Mt. Klappan anthracite (Sample A1) from 498°C to 561°C. The combustion temperature range of anthracite, however, can be lowered by reducing the particle size. Micronized anthracite (Sample A2) shows a combustion temperature from 475°C to 535°C. It is obvious from these data that Coal Valley coal burns in a distinctly different combustion temperature range while Goodrich and Mt. Klappan have overlapping combustion temperature ranges. The combustion temperatures for the coal samples tested at their various stages of combustion are presented in Table 4 and illustrated in Figure 3.

It was shown in a previous study (1) that when coal samples of distinctly different combustion temperature ranges are mixed, there is little synergism in combustion. The TGA thermograms of these coal mixtures are basically additives of the thermograms from the individual coal samples. The onset temperature (T_{xo}) of the mixtures is basically determined by the more reactive coal; and the completion temperature (T_{xc}) is controlled by the inert component. Figure 4 shows the TGA derived combustion temperatures of Coal Valley/Mt. Klappan mixtures at various blend ratios from the previous study.

This present project concentrates on the investigation of combustion temperatures of mixtures of coal samples of overlapping combustion temperature ranges (Goodrich and Mt. Klappan). The TGA thermograms of these coal mixtures do not show the additive nature of component thermograms and the TGA derived combustion temperatures also exhibit a somewhat different trend. The onset temperatures of coal mixtures is not governed by the Goodrich component but increase as the anthracite component increases; while the completion temperatures also increase as the anthracite component increases to about 50 Wt%. Above 50 Wt%, the completion temperature is controlled by the more inert component. Temperatures for 25%, 50%, and 75% combustion levels show a progressively diminishing interaction of coal component as the temperatures change from T_{xo} to T_{xc}. These combustion temperatures are shown in Tables 5, 6 and 7 and Figures 5 and 6 for mixtures of thermal coals and Mt. Klappan anthracites of conventional and micronized grinds.

5.2 Differential Scanning Calorimetry (DSC)

All the individual coal samples were evaluated by differential scanning calorimetry (DSC) to provide supporting data to the TGA combustion profiles. DSC measures heat flow as a function of temperature. As such, DSC provides complimentary data to the thermogravimetric analysis. DSC profiles for the individual coals are attached in Appendix 4.

Table 8 compares the onset combustion temperatures (TXO) by TGA and DSC, and Table 9 compares the temperatures of maximum mass loss, the TGA inflection temperatures (Ti), and the DSC maximum heat flow determined by these two methods. It is observed that in both cases there are a high degree of correlation.

5.3 Entrained Flow Combustor (EFC) Evaluation

Bench scale combustion evaluation using a laboratory scale entrained flow combustor (EFC) was subcontracted to Alberta Research Council (ARC). Flammability temperatures and carbon burnouts were determined for individual coals and coal mixtures. The subcontractor report entitled "Evaluation of the Combustibility of Anthracite/Thermal Coal Mixtures" is attached in Appendix 5.

5.3.1 Flammability Temperatures

Flammability temperatures, as determined by ARC, following the procedures established by Combustion Engineering, measure the "ignition" temperature at which the rate of heat generation from combustion reactions exceeds the rate of heat loss of combusting particles. Heat loss depends on the configuration of the reactor, mixing, turbulence, etc. These temperatures are therefore reactor specific. However, they do provide a good indication of how easily various fuels can be ignited under the same operating condition.

The flammability temperatures of individual coals and coal mixtures are summarized in Table 10. Obed ignites at 457°C, Obed product (B1) at 448°C, Coal Valley coal at 401°C, Goodrich at 483°C, and micronized anthracite at

566°C. Anthracite of the conventional grind shows a flame at 650°C. It should be noted that Coal Valley coal ignites at the lowest temperature (401°C) while the conventional ground Mt. Klappan anthracite coal ignites at the highest temperature (650°C).

There appears to be reasonable correlation between the emprical and calculated flammability temperatures determined for the coal mixtures (Table 10). While the TGA evaluations show that there is little interaction for Coal Valley/Mt. Klappan anthracite mixtures but some interaction for Goodrich/Mt. Klappan anthracite mixtures, the EFC data indicate that the interaction does not depend on the combustion temperature range of the more reactive coals. Common combustion temperatures do not seem to be a deciding factor. Flammability temperatures of coal mixtures prepared from the more reactive coals and anthracites of different grinds also do not show the effect of a micronized fuel.

5.3.2 Carbon Burnout

Carbon burnout for individual coals and coal mixtures were determined in ARC's entrained flow reactor. Carbon burnout is expressed on a dry, ash free basis (daf) in this study and provides measurement of the reactivity of the carbonaceous materials.

Initial experiments were carried out in the EFC at 1100°C and 5% oxygen level. Under these conditions, bituminous coals gave reasonable carbon burnout, but anthracite samples showed little combustion. Combustion experiments were then carried out under more severe conditions: 1100°C, 21% oxygen, and longer particle residence time. The effect of oxygen content and particle residence time on carbon burnout for the Coal Valley and Goodrich samples is shown in Table 11. The percentage of carbon burnout of Coal Valley coal increased from 45% to 94%, but the combustion of Goodrich coal only increased from 30% to 58%, as the oxygen content was increased from 5% to 21% and particle residence time was increased from 0.12 seconds to 0.30 seconds in the EFC reactor.

Carbon burnout at 1100°C and 21% O_2 for all the individual coal samples are compared in Table 12. The particle residence time was estimated from a mathematical model at ARC. Even under the more severe conditions, anthracite samples required a longer residence time to achieve a carbon burnout that could be measured by analytical methods. Obed coal sample (0) and its beneficiated product (B1) had the highest percentage of carbon burnout followed by Coal Valley coal and the Goodrich coal sample. Based on the volatile release data, the combustion of anthracite of conventional grind was questionable because its weight loss at 0.36 sec residence time was equivelent to its volatile matter content. However, the carbon burnout of anthracite was improved from 9% to 36% by reducing its particle size to the micronized grind.

Carbon burnout for six coal mixtures are shown in Table 13 and compared with values calculated from individual components assuming linear additivity. When anthracite of conventional grind was used as the inert component, the measured burnout were less than the calculated burnout suggesting that anthracite inhibits the combustion of the more reactive thermal coals. This phenomenon was observed when Coal Valley and Goodrich coal were investigated as the other component. Combustion of coal mixtures prepared from micronized grind, however, gave carbon burnout in good agreement with the calculated values. This suggests that coal components were combusted individually in the EFC experiments.

5.4 Correlations of TGA/DSC/EFC Data

Combustion temperatures of individual coal samples determined by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) are in good agreement. This is because of the virtually identical environment used in both techniques. Correlations of the onset temperatures from TGA and DSC are shown in Figure 7. The relationship between TGA's inflection temperature and DSC's temperature of maximum heat flow is presented in Figure 8.

The absolute values of TGA's onset temperatures do not agree with EFC's flammability temperatures. The flammability temperatures of individual coals are always higher than the TGA onset temperature. However, the ease of

ignition of individual coals showed the same trend by both combustion methods. The relationship between these temperatures is shown in Figure 9. The differences of ignition temperature in absolute terms are probably due to the different environments and physical conditions utilized in these two methods. Coal particles are subjected to a more rapid heating rate, more oxygen surrounding, and are governed by reactor configurations in heat loss in the EFC experiments.

Onset temperatures of coal mixtures by TGA techniques showed that their magnitudes depended on the existence of overlapping combustion temperatures. Anthracite/Goodrich mixtures showed increases in onset temperature as the anthracite component increased; but the onset temperatures of Anthracite/Coal Valley mixtures were basically controlled by the more reactive component. Onset temperatures determined by TGA on Goodrich/Micronized Anthracite mixture also showed the effect of micronized grind in combustion.

The flammability temperatures of coal mixtures determined in ARC's EFC showed that their magnitudes did not rely on overlapping combustion temperatures. Flammability temperatures compared very well with the calculated values from individual components. Flammability temperatures of coal mixtures using micronized grind also did not show the benefit of reducing particle size.

Reactivity of carbonaceous materials was determined by carbon burnout in ARC's EFC. Experiments on individual coals showed that the reactivity decreased from Obed and Obed Product to Coal Valley, Goodrich, and Mt. Klappan Anthracite. Conventional ground Mt. Klappan Anthracit appeared to inhibit combustion of more reactive thermal coals; while micronized ground anthracite did not appear to inhibit the combustibiltiy of the mixtures. The interactions of coal components in the initial phase of combustion (as determined by flammability index) and those in the final stage (as determined by carbon burnout) appeared to be controlled by different mechanisms.

6. CONCLUSIONS

1. The Thermogravimetric Analysis (TGA) volatile release profiles provide basic information on the amount of "reactive" components present in a coal sample. These reactive components determine the ease of ignition. The bituminous coals, which released volatile matter at a lower temperature and at a faster rate, are easier to ignite than anthracite.

2. Volatile release can be enhanced by reducing the particle size of a coal sample. The micronized anthracite sample released more volatile matter and ignited and burned at lower temperatures than its counterpart of conventional grind.

3. The relative ease of ignition of coal samples can be assessed by thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), or by a bench scale entrained flow combustor (EFC). The onset temperatures determined by TGA and DSC using the same environment, are in excellent agreement. The difference between TGA onset temperatures and flammability temperature in the EFC is believed to be caused by the different environment used in these methods.

4. The inflection temperature from TGA (maximum rate of weight loss) and the temperature of maximum heat flow from DSC correlate quite well.

5. Some interaction of combustion is observed in TGA when coal samples of overlapping combustion temperature ranges are mixed. There is little synergism in combustion when coal samples of distinctly different combustion temperatures are blended together.

6. Interaction of combustion based on flammability temperatures determined for coal mixtures in the EFC show that overlapping combustion temperatures are not a deciding factor.

7. The results of EFC flammability temperatures indicate the benefits of micronized grind when the individual sample is combusted. This benefit is not revealed when coal mixtures, using a component of micronized grind, are investigated.

8. The results of carbon burnout of individual coals (EFC Experiments) show that Obed and its upgraded product give the highest combustion efficiency. Their combustion reactivity is followed by Coal Valley, Goodrich and Mt. Klappan Anthracite.

9. The results of carbon burnout of coal mixtures show that when anthracite of conventional grind is used as a component, it inhibits combustion. However, when micronized anthracite is used, the coal particles appear to be combusted individually.

7. RECOMMENDATIONS

The results reported here are based on combustion evaluations using bench scale techniques. TGA, DSC, and EFC data correlate well in the assessment of the relative ease of ignition of the individual coal samples.

However, the applications of these techniques for coal mixtures give inclusive results. TGA data indicate that a common combustion temperature range is required for combustion interaction; but EFC data do not confirm this observation. Whether the coal component burns individually or collectively in a EFC is also not clearly revealed.

It is recommended that a larger scale burn test be undertaken to evaluate combustion properties of these coal mixtures. A coal mixture of Goodrich and anthracite is recommended for this study. The determinations of ignition, flame stability and carbon burnout is essential in assessing the merits of coal blending in combustion.

8. REFERENCES

1. B.Y. Wong, March 1986. "Evaluation of Combustion Options for Anthracite Utilization". D.S.S. File #06SQ.23440-5-9078, Final Report.

TABLE 1

PROXIMATE AND ULTIMATE ANALYSIS OF COAL SAMPLES

	Mt.Klappan A1	Coal Valley C	Goodrich G
% Residual Moisture	3.42	7.44	2.24
% Ash	9.97	10.33	11.76
% Volatile Matter	8.03	33.77	23.66
% Fixed Carbon	78.58	48.46	62.34
Calorific Value (cal/g)	7189	6135	7122
Fuel Ratio (FC/VM)	9.78	1.44	2.63
% Carbon		67.73	75.98
% Hydrogen		3.10	3.96
% Nitrogen		0.88	1.11
% Sulfur		0.218	0.26
% Ash		10.33	11.76
% Residual Moisture		7.44	2.24
% Oxygen (by difference)		10.31	4.69

TABLE 2

PROXIMATE AND ULTIMATE ANALYSES OF TEST SAMPLES (ARC)

	A1	A2	G	C	O	B1
Ultimate (daf)						
C	92.2	91.9	86.2	77.7	76.5	77.9
H	2.4	2.4	4.3	4.4	5.2	4.9
N	1.4	1.4	1.6	1.2	1.7	1.8
S	0.6	0.5	0.3	0.3	0.8	1.0
O (diff)	3.4	3.8	7.6	16.4	15.8	14.4
Proximate						
Moisture	2.5	2.9	2.0	8.2	11.2	1.5
Ash (dry)	11.2	10.5	11.7	11.1	14.9	13.7
VM (daf)	8.1	9.0	25.1	36.2	43.6	39.1
FC (daf)	91.9	91.0	74.9	63.8	56.4	60.9

A1 – Mt. Klappan Anthracite, Conventional Grind
A2 – Mt. Klappan Anthracite, Micronized Grind
G – Goodrich
C – Coal Valley
O – Obed
B1 – Upgraded Obed

TABLE 3

SUMMARY OF MASS LOSS AT DIFFERENT TEMPERATURES IN VOLATILE RELEASE PROFILES

Sample	% Wt. Loss (Cumulative) at 200°C	300°C	400°C	500°C	900°C
A1 (ref 1)	---	0.7	1.0	1.5	7.3
A2	---	1.1	1.4	1.6	7.6
C	1.0	1.0	4.0	17.0	32.0
G	0.0	1.0	2.0	10.0	21.5
O	2.0	2.5	4.5	18.5	31.5
B1	0.7	2.2	4.7	19.2	34.7

TABLE 4

SUMMARY OF TGA DERIVED COMBUSTION TEMPERATURES OF INDIVIDUAL COALS

Sample File #	Sample	T_{xo}	T_i	T_{xc}	T_o	T_{25}	T_{50}	T_{75}
08	A1 (Anthracite)	498	530	561	340	518	537	558
09	A2 (Micronized	477	510	542	344	499	517	543
19	Anthracite)	473	496	527	344	496	511	537
	average	475	503	535	344	497	514	540
04	G (Goodrich)	418	450	495	300	446	470	505
21		419	454	495	296	445	468	505
	average	418	452	495	298	445	469	505
03	C (Coal Valley)	381	411	425	252	391	414	432
	O (Obed)	352	389	424	--	365	390	415
	B1 (Beneficiated Obed)	360	393	428	--	375	400	420

TABLE 5

SUMMARY OF TGA DERIVED COMBUSTION TEMPERATURES
A1 AND C (Anthracite 250μm x 0 AND COAL VALLEY COAL)
(REF 1)

Sample File #	Composition (% anthracite)	T_{xo}	T_i	T_{xc}	T_o	T_{25}	T_{50}	T_{75}
8	100 (pure Anthracite)	502	537	572	398	525	540	565
7	75	396	431 538	570	274	470	530	555
6	50	393	422 542	572	250	425	495	545
24	25	381	410 544	573	240	410	430	505
3	0 (pure Coal Valley)	354	376	424	228	375	395	420

TABLE 6

SUMMARY OF TGA DERIVED COMBUSTION TEMPERATURES
A1 AND G (Anthracite 250μm x 0 AND GOODRICH COAL)

Sample File #	Composition (% anthracite)	T_{ro}	T_i	T_{xc}	T_o	T_{25}	T_{50}	T_{75}
08	100 (pure Anthracite)	498	530	561	340	518	537	558
10	75	471	523	560	318	493	524	552
11	50	463	523	556	315	486	518	545
12	25	429	470	527	308	461	491	537
15	25	428	471	530	308	460	490	533
	average	428	470	528	308	460	490	535
04	0 (pure Goodrich)							
21		418	450	495	300	446	470	505
		419	454	495	296	445	468	505
	average	418	452	495	298	445	469	505

TABLE 7

SUMMARY OF TGA DERIVED COMBUSTION TEMPERATURES A2 AND G (Anthracite 45μm x 0 AND GOODRICH COAL)

Sample File #	Composition (% anthracite)	T_{ss}	T_i	T_{sc}	T_o	T_{25}	T_{50}	T_{75}
09	100 (pure micronized	477	510	542	344	499	517	543
19	anthracite)	473	496	527	344	496	511	537
	average	475	503	535	344	497	514	540
23	75	462	500	536	320	487	509	535
17	50	441	495	542	308	474	504	535
18	25	432	477	525	306	463	490	526
04	0 (pure Goodrich)	418	450	495	300	446	470	505
21		419	454	495	296	445	468	505
	average	418	452	495	298	445	469	505

TABLE 8

COMPARISON OF ONSET COMBUSTION TEMPERATURE BY TGA AND DSC

	A1	A2	C	G	B1	O
TGA (°C)	498	477	381	418	360	352
DSC (°C)	482	471	402	419	--	--

TABLE 9

COMPARISON OF COMBUSTION TEMPERATURE OF MAXIMUM MASS LOSS AND MAXIMUM HEAT FLOW BY TGA AND DSC

	A1	A2	C	G	B1	O
TGA* (°C)	530	503	411	452	393	389
DSC** (°C)	560	542	440	500	405	410

* Inflection temperature (T_i)

** Temperature of maximum heat flow

TABLE 10

FLAMMABILITY TEMPERATURES FOR COAL SAMPLES AND COAL MIXTURES

Sample	Flammability Index (°C)	Calculated Flammability Index
C	401	--
B1	448	--
O	457	--
MII	475	483
MI	480	525
G	483	--
MIII	535	567
MIV	535	525
A2	497* – 566+	--
A1	550* – 650+	--

* 'Sparking' observed but no flame

\+ used for calculated Flammability Index

MI	50 A1: 50 C
MII	50 A2: 50 C
MIII	50 A1: 50 G
MIV	50 A2: 50 G
MV	25 A2: 75 C
MVI	25 A2: 75 G

TABLE 11

EFFECT OF O_2 CONTENT AND RESIDENCE TIME ON CARBON BURNOUT AT 1100°C

Estimated Residence Time (sec)	Carbon Burnout % (daf)					
	C			G		
	5% O_2	21% O_2	% Increase	5% O_2	21% O_2	% Increase
0.12	45.2	91.9	103	30.4	44.0	45
0.18	42.5	91.0	114	30.4	47.2	55
0.24	54.6	96.4	76	34.4	52.5	53
0.30	--	93.7	--	33.6	57.8	72

C – Coal Valley sample

G – Goodrich sample

TABLE 12

CARBON BURNOUT AT 1100 °C & 21% O_2

Estimated Residence Time (sec)	Carbon Burnout % (daf)					
	A1	A2	C	G	B1	O
0.12	--	--	91.9	44.0	97.1	96.4
0.18	--	20.1	91.0	47.2	98.3	98.7
0.24	--	31.3	96.4	52.5	99.2	99.2
0.30	0.9	37.7	93.7	57.8	--	--
0.36	9.1	35.6	--	--	--	--

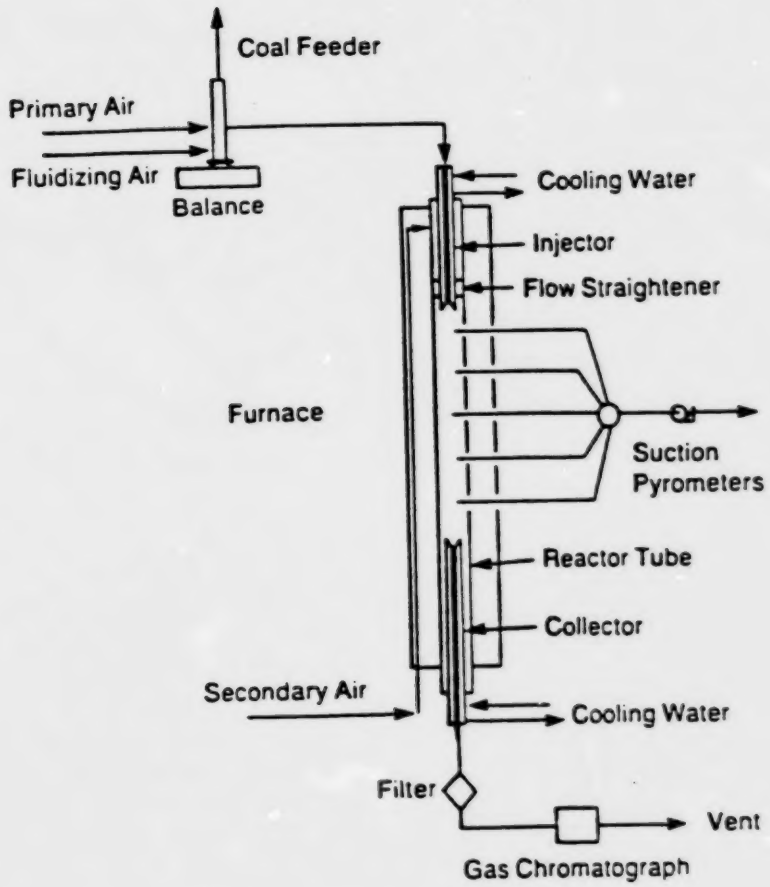
TABLE 13

CARBON BURNOUT OF COAL MIXTURES AT 1100°C AND 21% OXYGEN

Sample	Residence Time (sec)	Measured Burnout (wt.% daf)	Calculated Burnout (wt.% daf)
MI	0.18	19.3	45.5
50 A1: 50 C	0.24	37.4	48.2
	0.30	41.6	47.3
MII	0.18	57.1	55.6
50 A2: 50 C	0.24	65.3	63.9
	0.30	63.3	64.7
MIII	0.18	0.0	23.6
50 A1: 50 G	0.24	13.3	26.2
	0.30	25.0	29.4
MIV	0.18	36.0	33.7
50 A2: 50 G	0.24	40.8	41.9
	0.30	47.7	47.8
MV	0.18	79.5	73.3
25 A2: 75 C	0.24	80.8	80.1
	0.30	80.9	79.7
MVI	0.18	42.2	38.0
25 A2: 75 G	0.24	48.7	47.2
	0.30	52.8	52.8

FIGURE 1

Drop Tube Combustor



Sample: 50% A2 50% CV
Size: 34.12 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 10-Feb-86 Time: 9:38:43
File: COAL/ANTH.16 COAL TGA/GC.01
Operator: 347-85-85
Plotted: 11-Feb-86 14:41:56

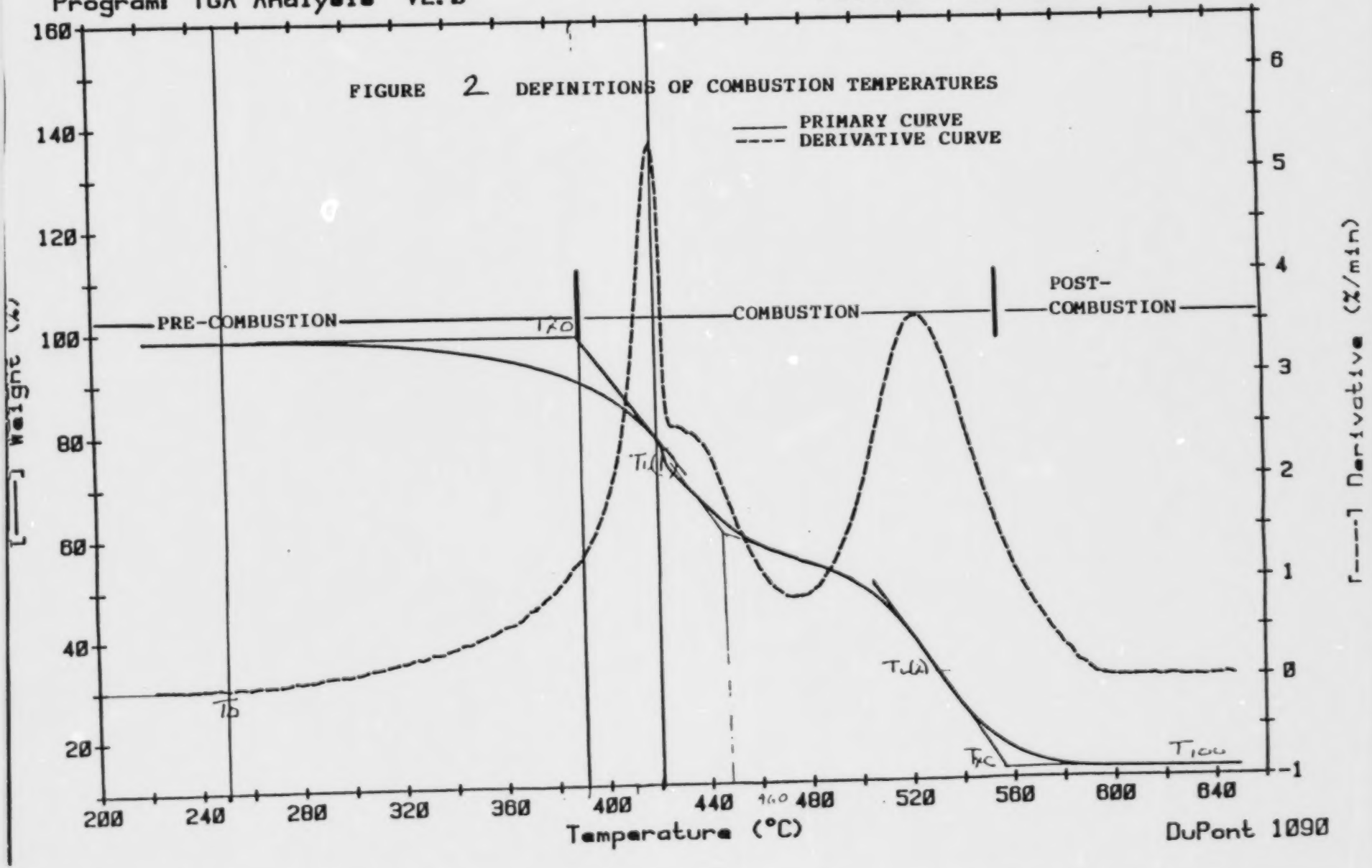


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FIGURE 3
Combustion Temperatures of Individual Coals

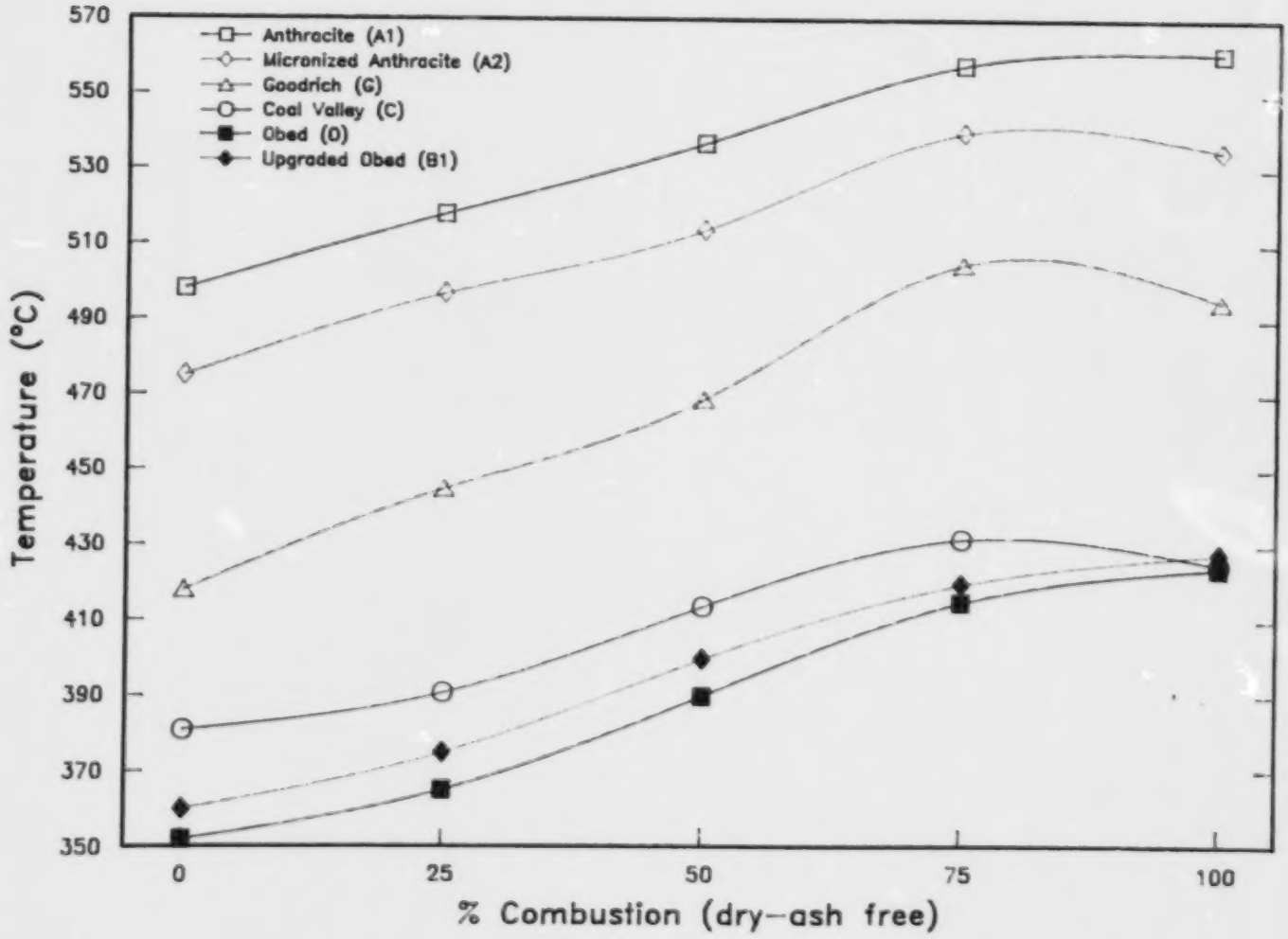


FIGURE 4
Combustion Temperature of Coal Mixtures – C & A1

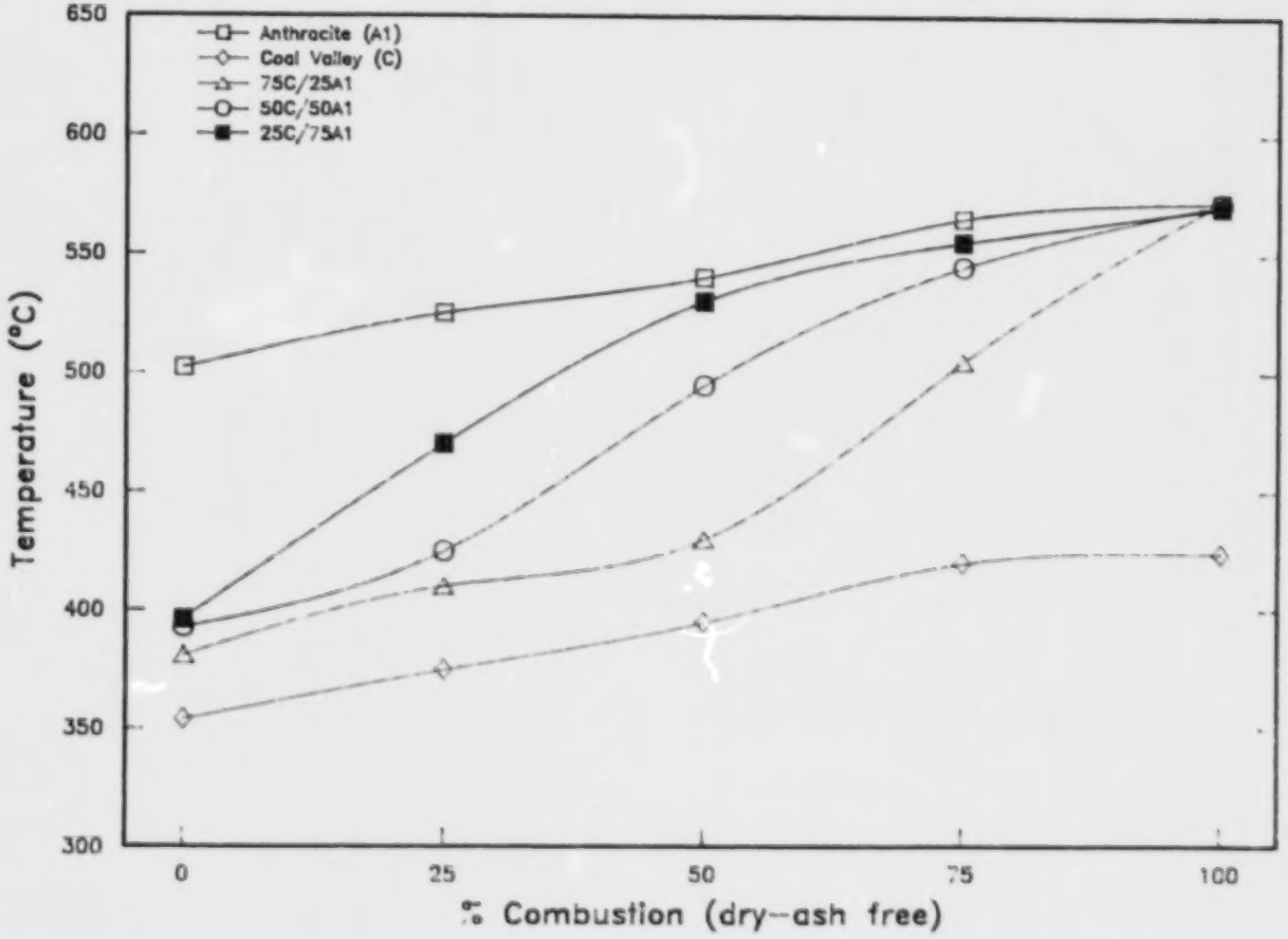


FIGURE 5
Combustion Temperature of Coal Mixtures – G & A1

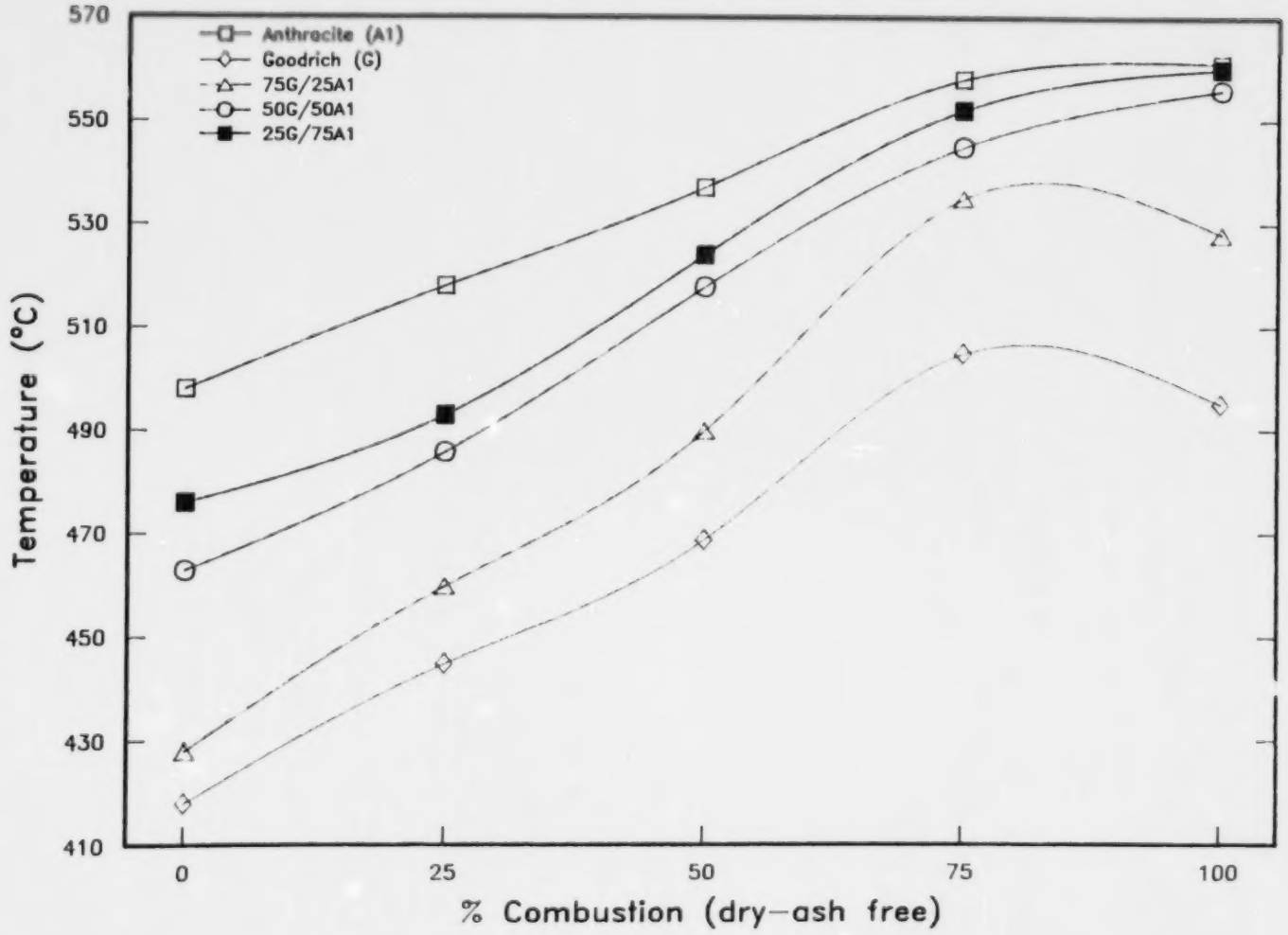


FIGURE 6
Combustion Temperature of Coal Mixtures – G & A2

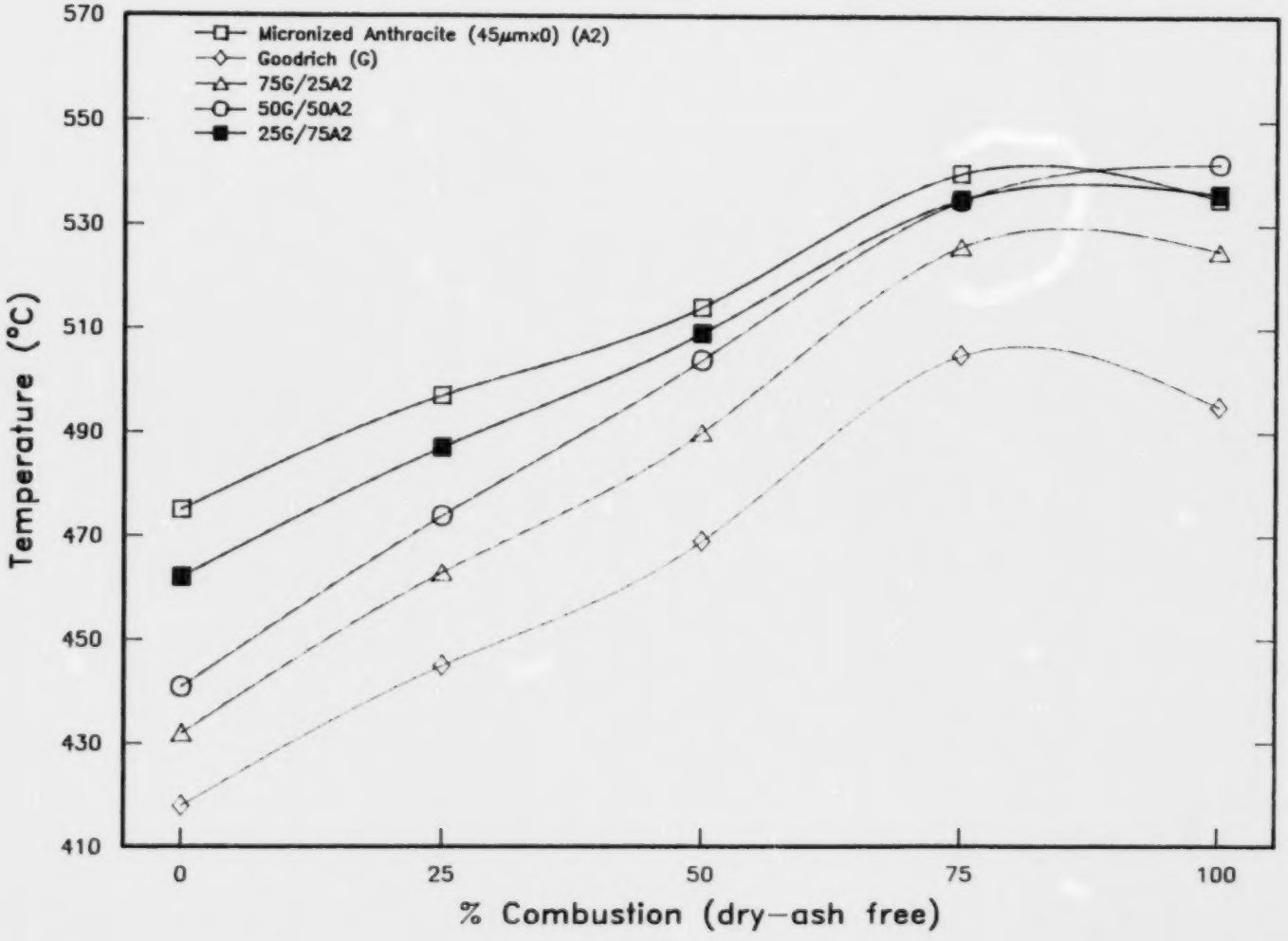


FIGURE 7
Comparison of Onset Combustion Temperature by TGA and DSC

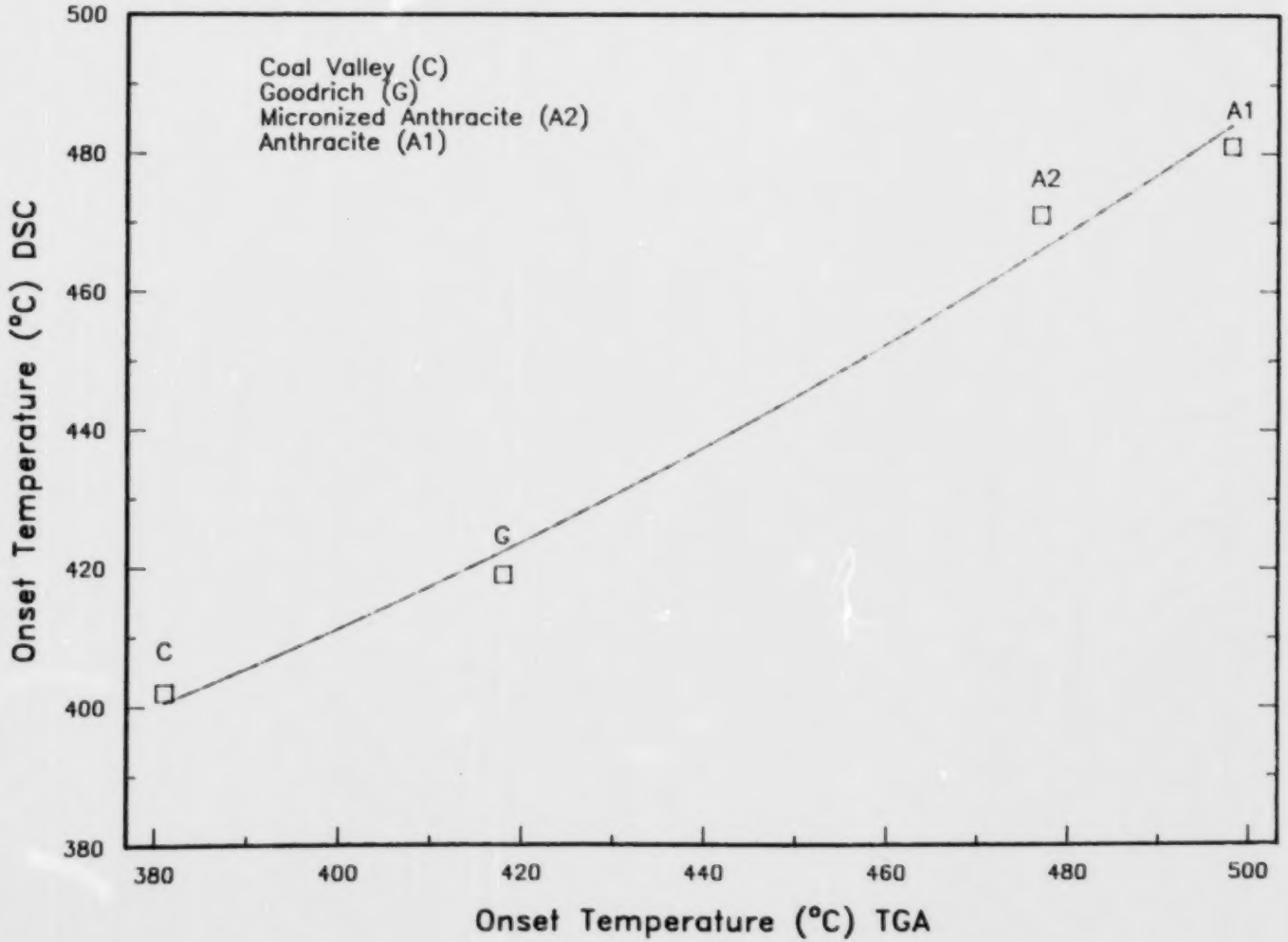


FIGURE 8
Comparison of Combustion Temperature of Maximum Mass Loss and Maximum Heat Flow by TGA and DSC

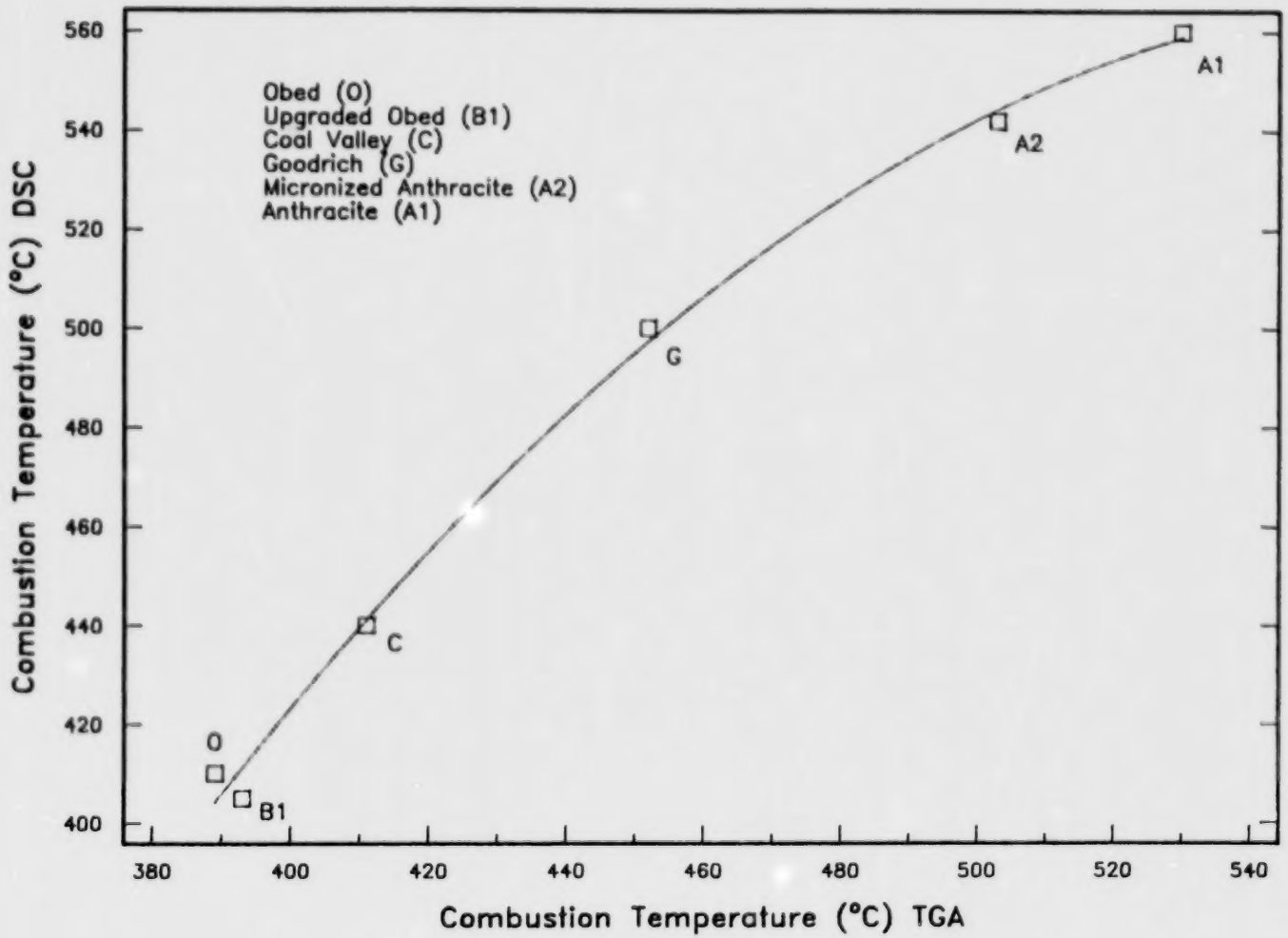
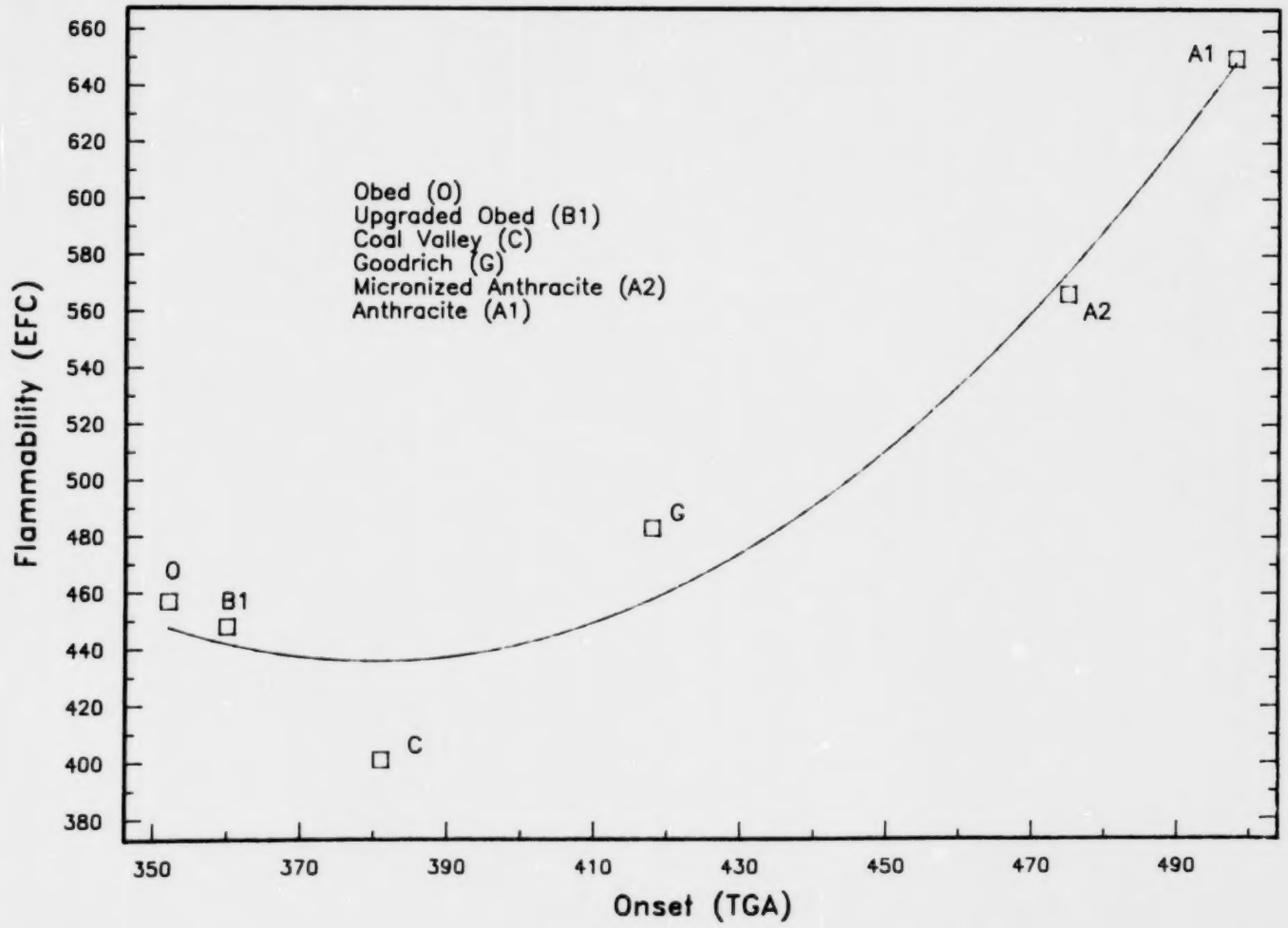


FIGURE 9
Comparison of Onset Temperature (TGA)
and Flammability Temperature (EFC)



APPENDIX 1

Work Statement

APPENDIX "A"

STATEMENT OF WORK

TITLE: BENCH-SCALE EVALUATION OF ANTHRACITE/THERMAL COAL MIXTURES FOR A PULVERIZED FIRING SYSTEM (Part of Energy, Mines & Resources 50/50 Cost Shared Energy Conversion Program)

Task 1 Acquisition and Analysis of Coal Samples

This task covers the work required to obtain, prepare and analyze all the samples for this research program. Approximately 25 kg of each coal sample will be acquired. Gulf Canada will be responsible to acquire the anthracite sample from Mt. Klappan, and CANMET will provide the Coal Valley sample and the Goodrich sample which has a different combustion range than Coal Valley. In addition, two beneficiated coal samples with residuum using Obed Marsh and Wabamun coals will also be used to assess the benefits of upgrading in combustion. These samples will be produced from Gulf's coal beneficiation program.

All the samples will be prepared to 250 µmxo and an additional micronized grind (45 µmxo) will be prepared for anthracite. These samples will be subjected to proximate and ultimate analyses, and calorific value determination. Preparation and analysis will be subcontracted out to Loring Laboratories in Calgary.

Task 2 TGA Experiments and Bench Scale Combustion Evaluation

This task covers combustion evaluation of coals and coal mixtures by TGA/DSC (thermogravimetric analysis and differential scanning calorimetry methods) and bench scale experiments. The TGA/DSC work will provide information on temperature of initial combustion; and bench scale experiments will establish data on carbon burnout. The results of these two methods will supplement each other.

TGA/DSC will be performed on anthracite/Goodrich mixtures which were not previously investigated in D.S.S. Contract OSQ.85-999176. Mixtures of compositions similar to those used in the above mentioned contract will be examined. Combustion profiles, supporting data from DSC, and volatile release profiles of individual coals will be determined.

Approximately 15-20 experiments will be carried out. Another 10 experiments will also be carried out to provide back-up information such as determinations of volatile and combustion profiles of the beneficiated products.

ELIMINATION BEGINS

The bench scale combustion experiments will be use the combustion furnace designed and built by Gulf Canada. The major emphasis will be the determination of carbon burnout. A total of 24 experiments will be carried out. These consits of 6 individual coals, 14 coal mixtures and 4 replication. A tentative schedule for the bench scale evaluation program is presented below:

		Number of Experiments
I	Individual Coals	
	1. Anthracite (A_1)	1
	2. Micronized Anthracite (A_2)	1
	3. Coal Valley (C)	1
	4. Goodrich (G)	1
	5. Beneficiated Product I (B_1)	1
	6. Beneficiated Product II (B_2)	1
		6

II	Coal Mixtures	A_1+C	A_2+C	A_1+G	A_2+G	Number of Experiments
	Compositions	2	1	2	1	6
	Operating Conditions	2/4	2/3	2/4	2/3	8/14
III	Replications					4
	based on results from above coal blends				TOTAL	24

ELIMINATION ENDS

Task 3 Assessment of Results and Preparation of Final Report

A draft of the Final Report will be prepared and submitted to the Scientific Author of CANMET for approval. The final report will give a detailed description of the work performed under the project title "Bench Scale Evaluation of Anthractie Thermal Coal Mixtures for a Pulverized Coal Firing System" with the following information:

1. Background information of the objective, justification and usefulness of the project for Canada.
2. Experimental programs as detailed in Tasks 1 to 2.
3. Results and discussion as supported by tables, graphs and correlations.
4. Conclusion and recommendations.

Upon approval, 10 copies of the Final Report will be submitted to the Department of Supply and Services for Documentation.

APPENDIX "A"

STATEMENT OF WORK - AMENDMENT

AMENDED TASK 2

Task 2 TGA Experiments and Bench Scale Combustion Evaluation

This task covers combustion evaluation of coals and coal mixtures by TGA/DSC (thermogravimetric analysis and differential scanning calorimetry methods) and bench scale experiments. The TGA/DSC work will provide information on temperature of initial combustion; and bench scale experiments will establish data on carbon burnout. The results of these two methods will supplement each other.

TGA/DSC will be performed on anthracite/Goodrich mixtures which were not previously investigated in D.S.S. Contract OSQ.85-999176. Mixtures of compositions similar to those used in the above mentioned contract will be examined. Combustion profiles, supporting data from DSC, and volatile release profiles of individual coals will be determined.

Approximately 15-20 experiments will be carried out. Another 10 experiments will also be carried out to provide back-up information such as determinations of volatile and combustion profiles of beneficiated products.

The bench scale combustion evaluation will be subcontracted out to Alberta Research Council's Nisku Laboratories using their Entrained Flow Combustor.

To determine the relative flame stability of the coals and mixtures, a standard test procedure developed by Combustion Engineering will be used. Pulverized coals will be injected into a preheated gas stream at a carefully controlled temperature. The gas temperature will be raised incrementally until combustion of the coal is self supporting. The temperature will be defined as the Flammability Index. The value of the Flammability Index will indicate the relative flame ignition temperature and stability of the coals and mixtures.

The coal samples and mixtures will also be burned in the entrained flow combustor (EFC) to obtain a single burn profile for each fuel at conditions similar to those found in a utility boiler. These tests will provide information on carbon burnout rates and carbon in ash. The burnout profiles will be compared to determine the effect of mixing two coals on fuel combustibility.

Flammability Index

The -200 +230 mesh fraction will be injected into preheated oxygen through the EFC at carefully controlled gas temperature. The temperature will be raised in 20°C increments until ignition is observed. The ignition temperature will be determined within ±5°C for each sample. The micronized sample will be studied in a similar manner.

Combustion Tests

The -200 +230 mesh fractions and micronized sample will be injected into a preheated gas stream at a temperature of 1100°C containing 5% oxygen in nitrogen. Particles will be extracted from the reactor at three residence times from 60 to 250 ms and analyzed for ash content to determine the rate of carbon burnout.

By comparison of burnout profiles of pure coals with those of the 50/50 mixtures, the effect of mixing will be determined. If this effect is non-linear with component concentration, further experiments will be performed on 25/75 mixtures of interest. The following table shows the work plan for these evaluations.

Sample	Flammability Index	Entrained Flow Combustor
Anthracite (A1)	1	3
Micronized Anthractie (A2)	1	3
Coal Valley (C)	1	3
Goodrich (G)	1	3
Beneficiated Product I	1	3
Beneficiated Product II	1	3
Mixture I (50% A1 + 50% C)	1	3
Mixture II (50% A2 + 50% C)	1	3
Mixture III (50% A1 + 50% G)	1	3
Mixture IV (50% A2 + 50% G)	1	3
Mixture V (25% A1 + 75% C)*		
Mixture VI (75% A1 + 25% C)*		
Mixture VII (25% A1 + 75% G)*		
Mixture VIII (75% A1 + 25% G)*		
Replicates (based on results)	4	6

* These mixtures will be studied if burnout is non-linear with component concentration.

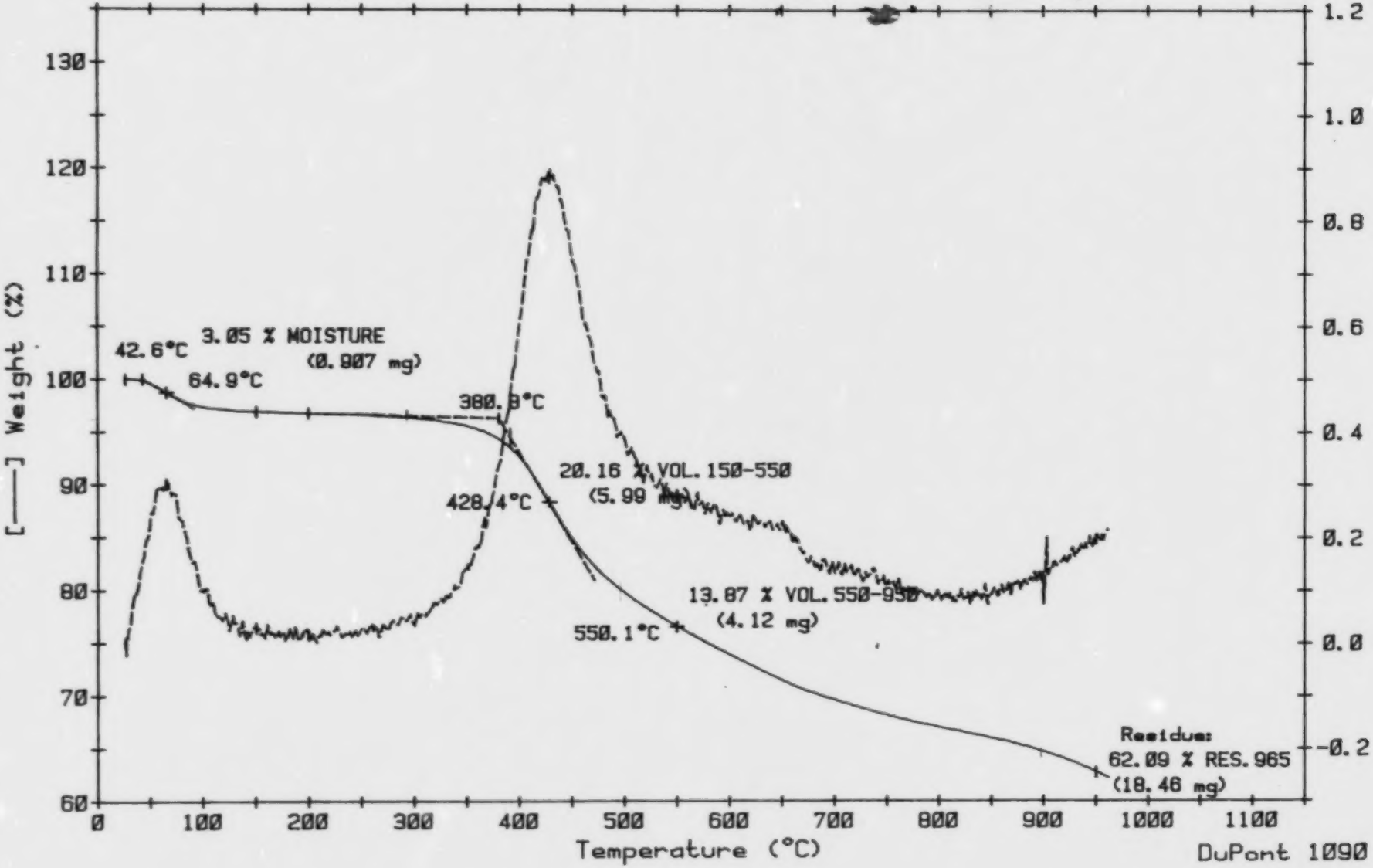
APPENDIX 2

Volatile Release Profiles

Sample: C VOL.REL
Size: 29.73 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0

TGA

Date: 13-Aug-86 Time: 14:10:35
File: COAL/ANTH.01 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 1:59:45



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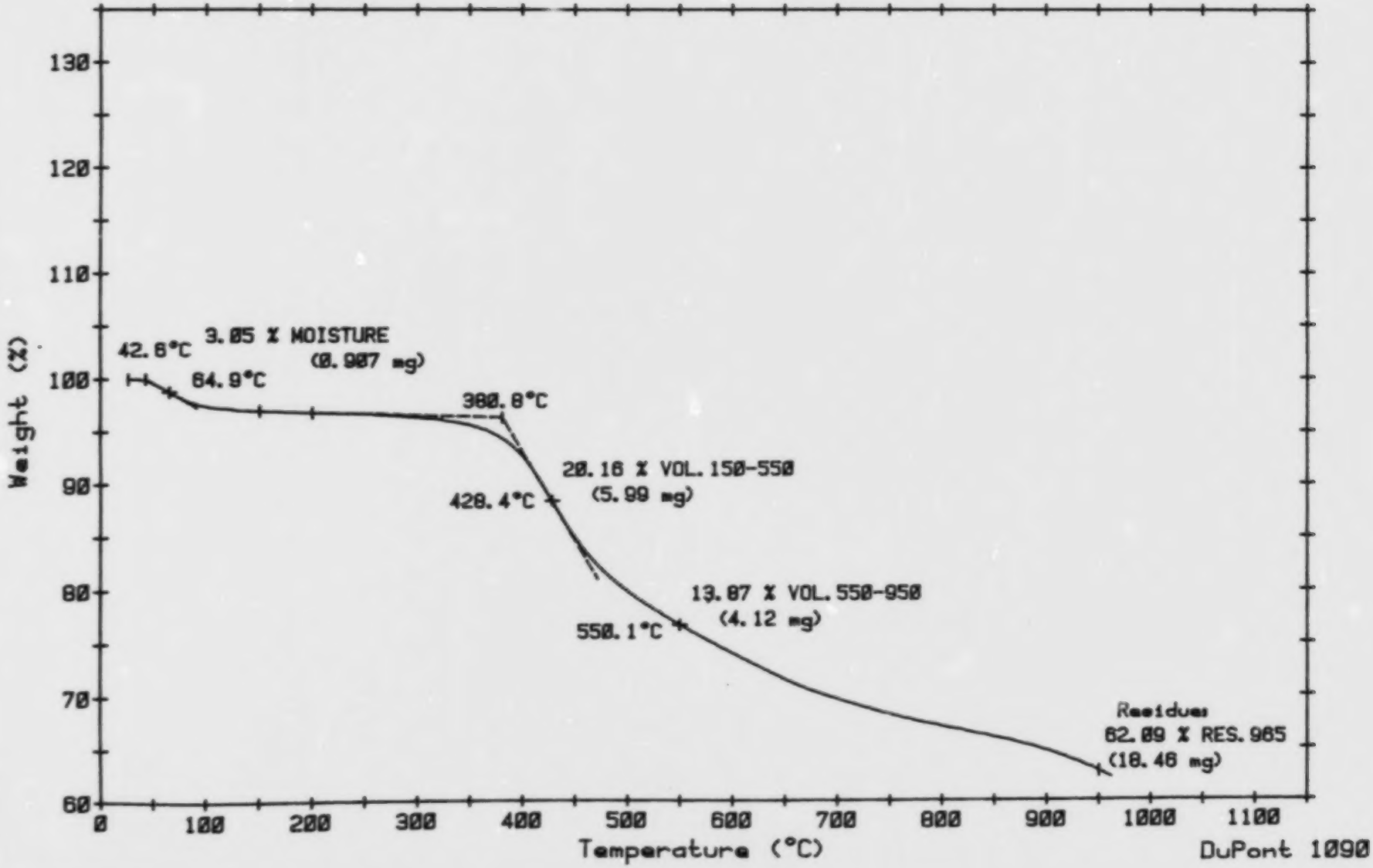
Sample: C VOL. REL
Size: 29.73 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0

TGA

Date: 13-Aug-86 Time: 14:10:35
File: COAL/ANTH.01 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 2:56:59

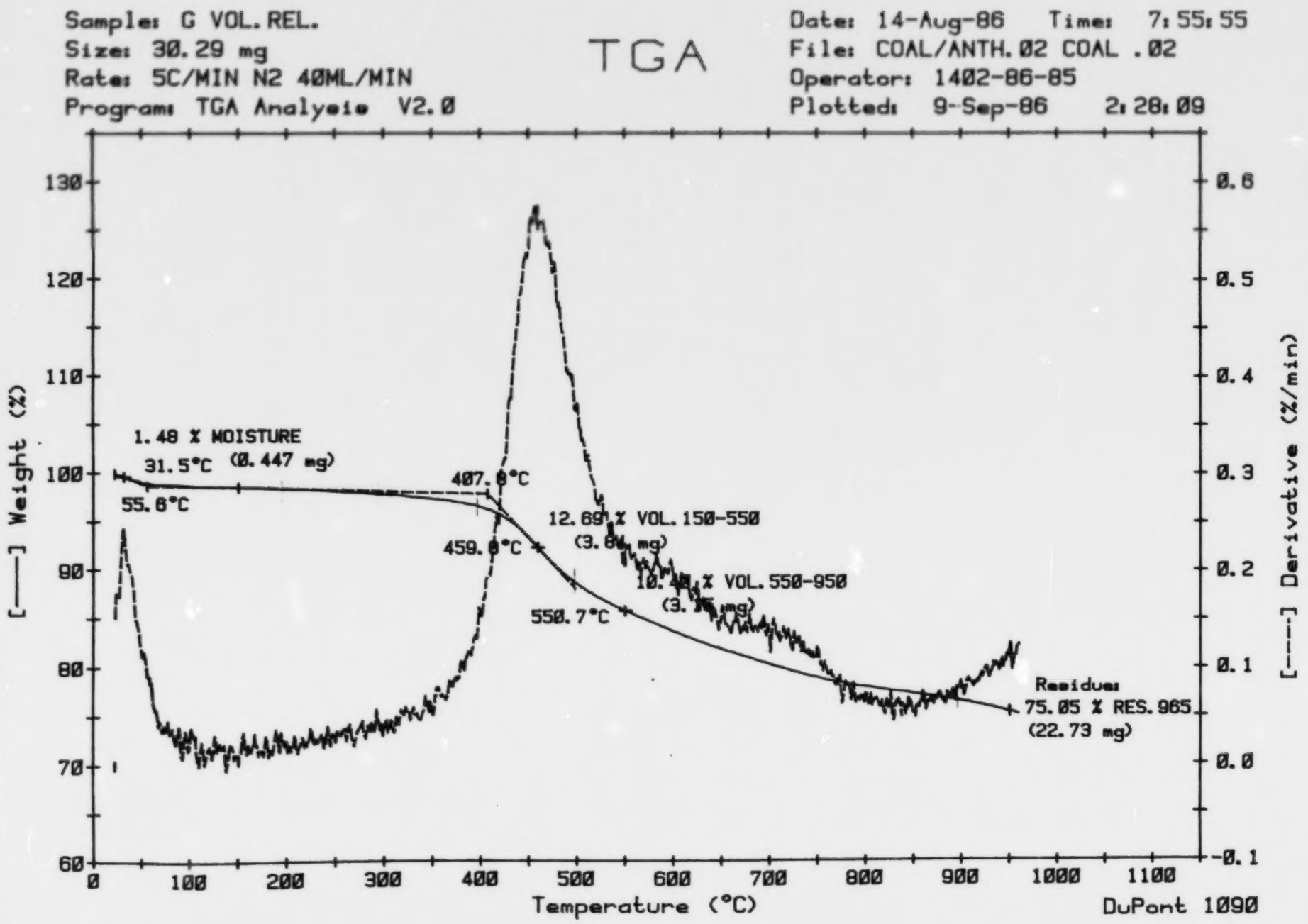


Sample: C VOL.REL
Size: 29.73 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0

Date: 13-Aug-86 Time: 14:10:35
File: COAL/ANTH.01 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 2:16:29

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE	42.6	64.9		0.91	3.05
VOL. 150-550	380.8	428.4		5.99	20.16
VOL. 550-950		550.1		4.12	13.87
RES. 965		Residue at 964.7 °C		18.46	62.09

Modified Sample Weight: 29.73 mg


Sample: G VOL.REL.
Size: 30.29 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0
TGA
Date: 14-Aug-86 Time: 7:55:55
File: COAL/ANTH.02 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 2:28:09
1.48 % MOISTURE
31.5°C (0.447 mg)
55.6°C
407.8°C
459.8°C
12.69 % VOL.150-550
(3.84 mg)
10.40 % VOL.550-950
(3.15 mg)
550.7°C
Residue:
75.05 % RES.965
(22.73 mg)
[——] Weight (%)
[----] Derivative (%/min)
Temperature (°C)
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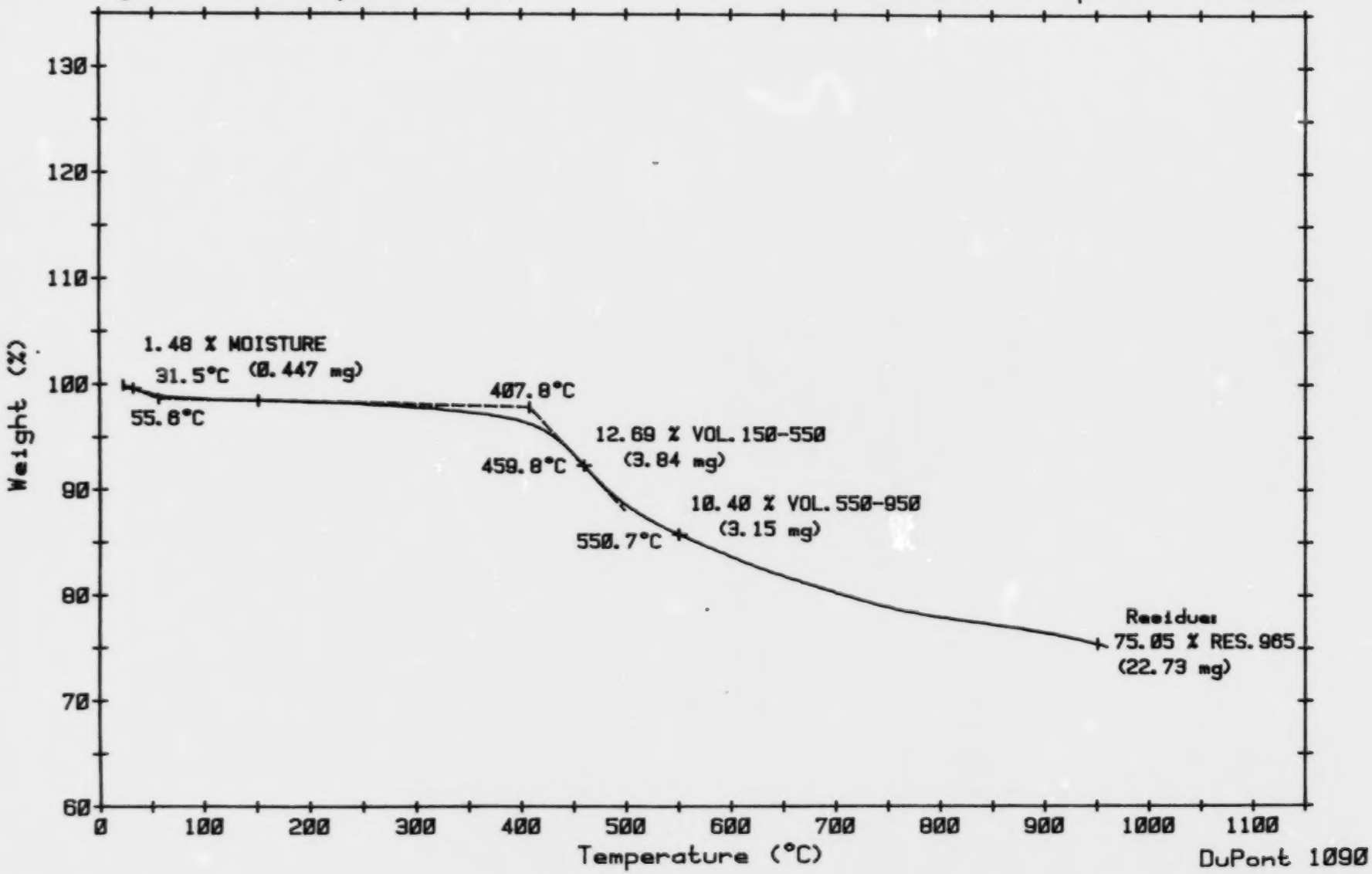
Sample: G VOL. REL.
Size: 30.29 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0

TGA

Date: 14-Aug-86 Time: 7:55:55
File: COAL/ANTH.02 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 2:42:27



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Sample: G VOL.REL.
Size: 30.29 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0

Date: 14-Aug-86 Time: 7:55:55
File: COAL/ANTH.02 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 2:45:47

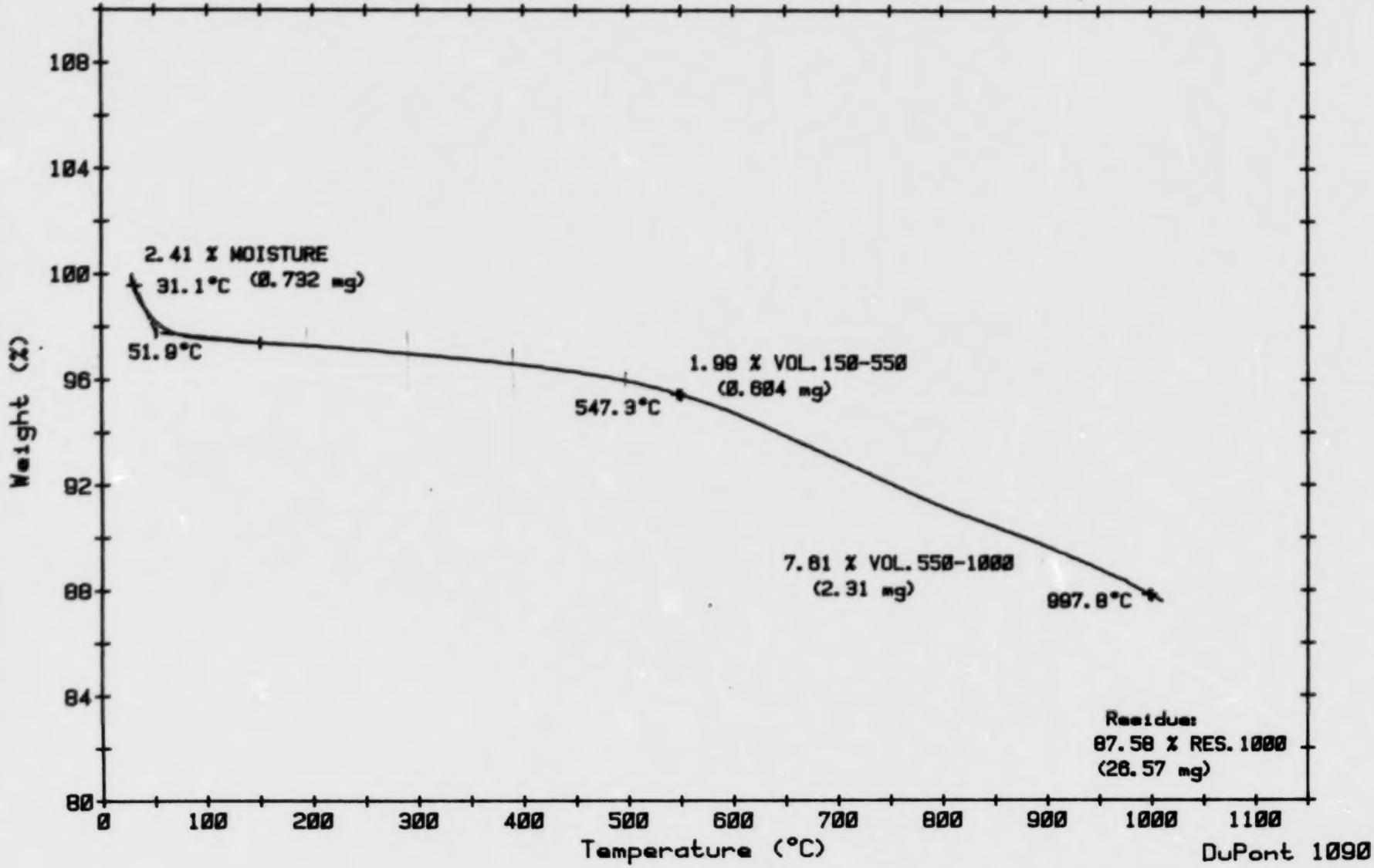
Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		31.5	55.6	0.45	1.48
VOL.150-550	407.8	459.8		3.84	12.69
VOL.550-950		550.7		3.15	10.40
RES.965		Residue at 962.3 °C		22.73	75.05

Modified Sample Weight: 30.29 mg

Sample: A2 VOL. REL.
Size: 30.34 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0

TGA

Date: 20-Aug-86 Time: 12:02:00
File: COAL/ANTH.07 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 3:51:33

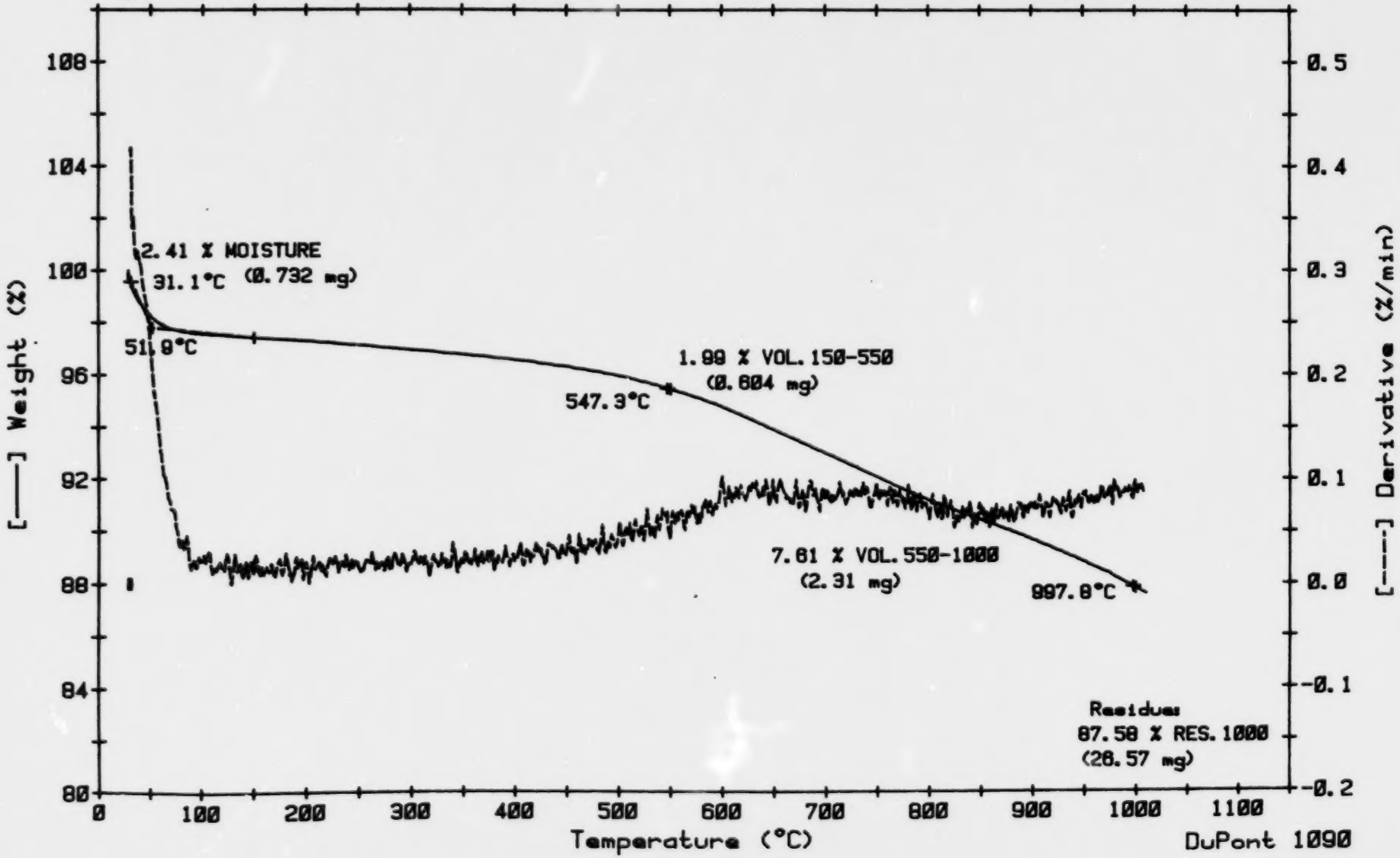


DuPont 1090

Sample: A2 VOL. REL.
Size: 30.34 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0

TGA

Date: 20-Aug-86 Time: 12:02:00
File: COAL/ANTH.07 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 3:40:20



DuPont 1090

Sample: A2 VOL. REL.
Size: 30.34 mg
Rate: 5C/MIN N2 40ML/MIN
Program: TGA Analysis V2.0

Date: 20-Aug-86 Time: 12:02:00
File: COAL/ANTH.07 COAL .02
Operator: 1402-86-85
Plotted: 9-Sep-86 3:56:56

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		31.1	51.9	0.73	2.41
VOL. 150-550		547.3		0.60	1.99
VOL. 550-1000		997.8		2.31	7.61
RES. 1000	Residue at 1010.7 °C			26.57	87.58

Modified Sample Weight: 30.34 mg

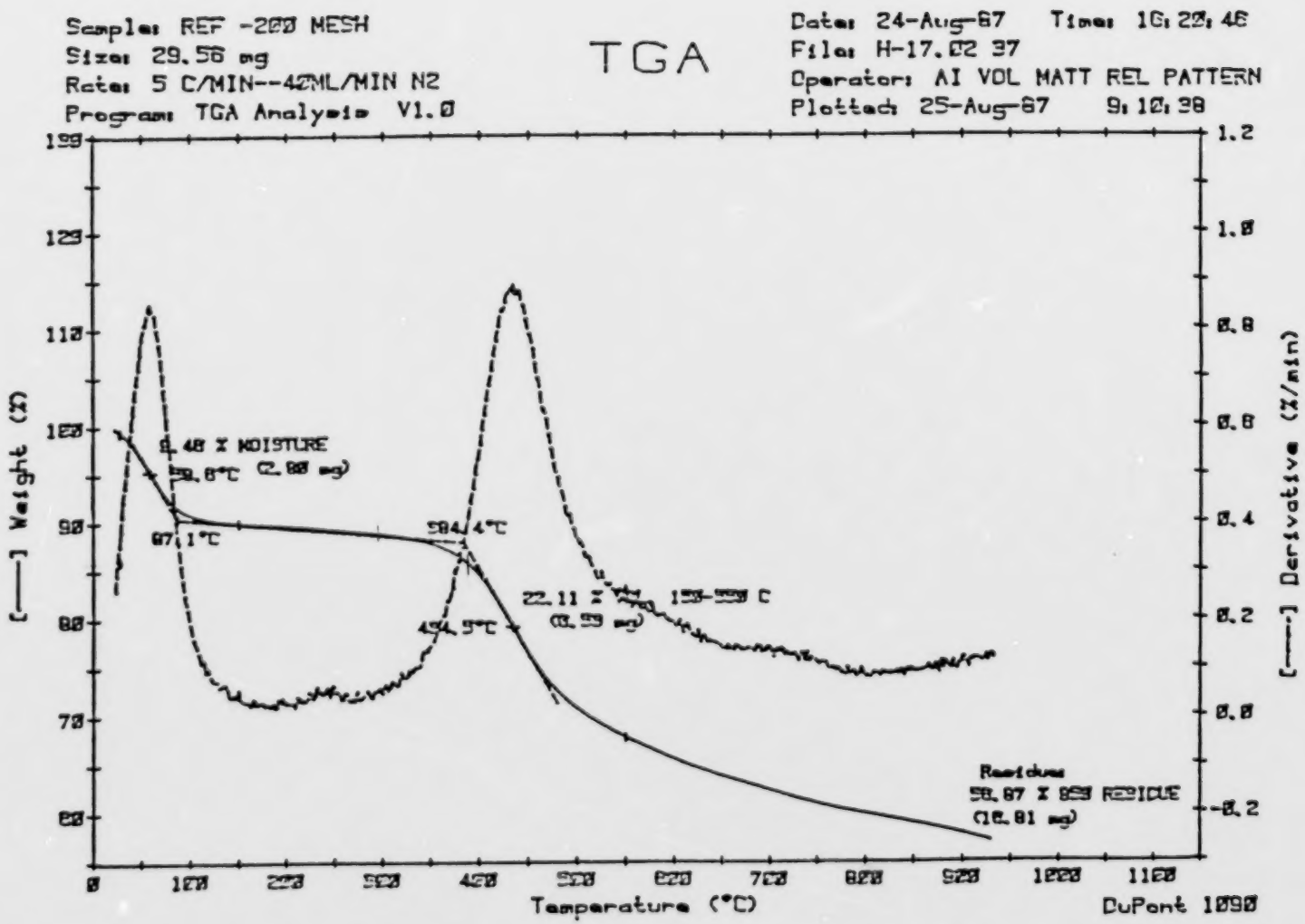


Figure 3.7 TGA Pyrolysis Profile for Sample O

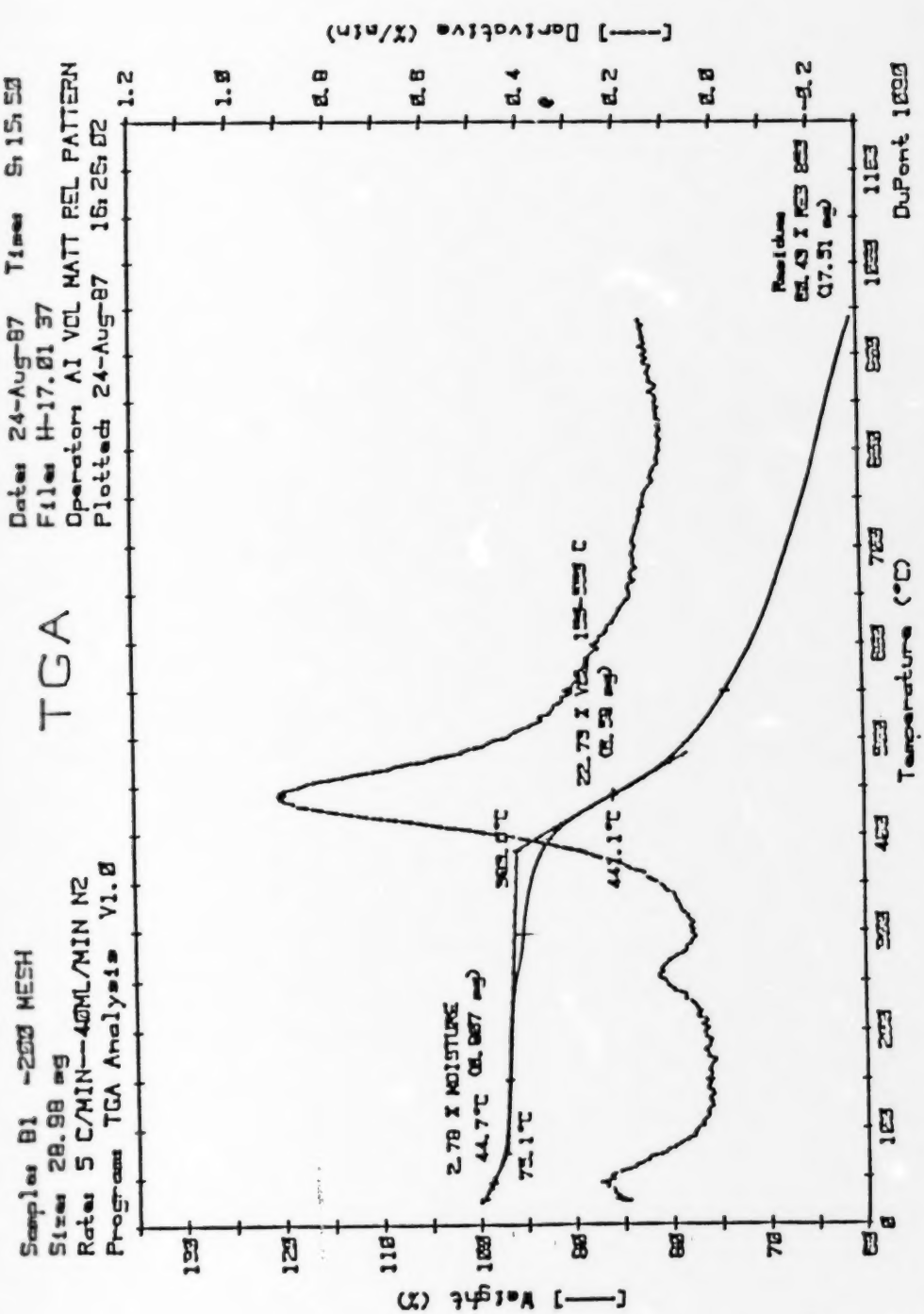


Figure 3.13 TGA Pyrolysis Profile for Sample B1

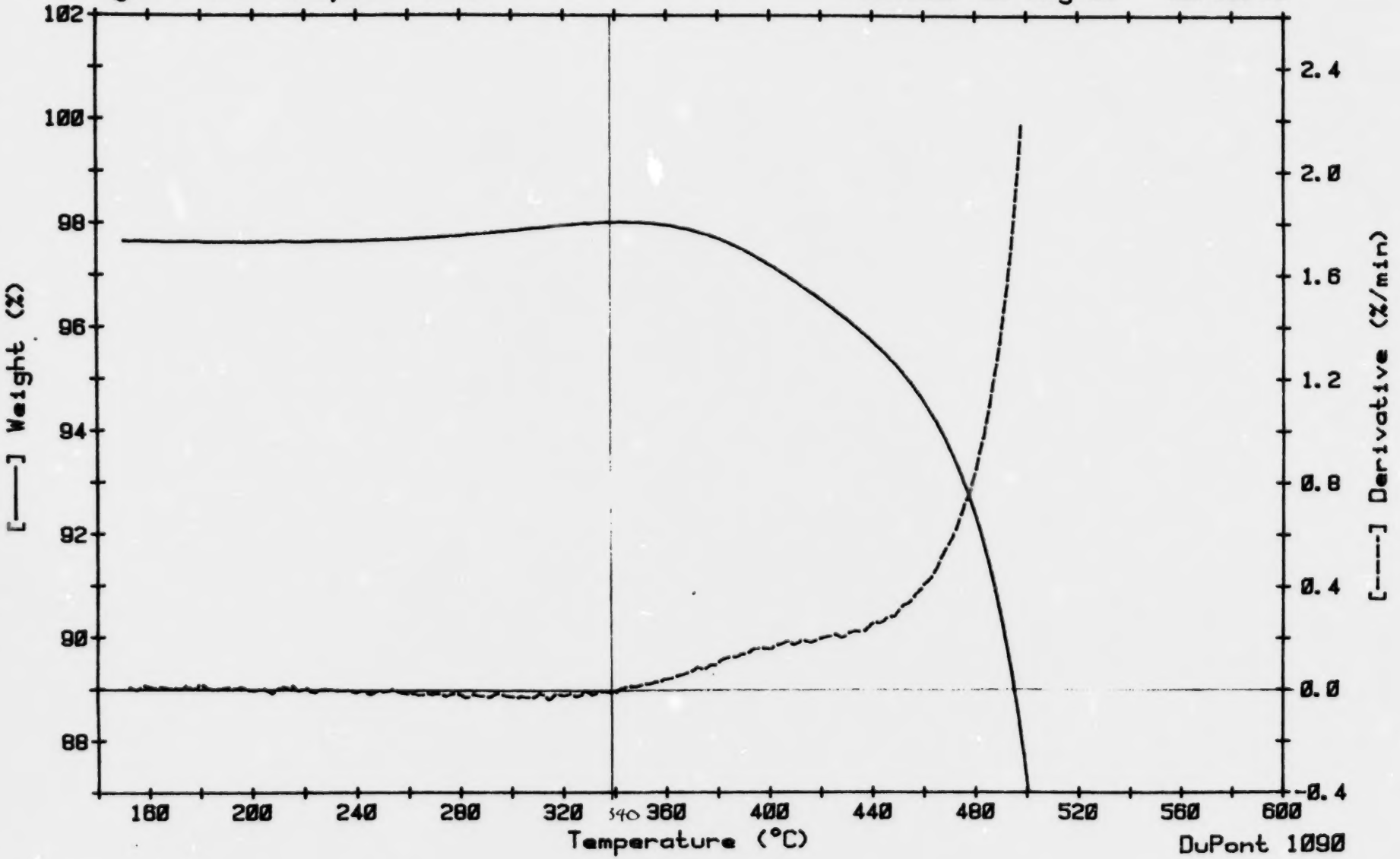
APPENDIX 3

TGA Combustion Profiles

Sample: A1 COMBUSTION
Size: 31.23 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 21-Aug-86 Time: 7:56:11
File: COAL/ANTH.08 COAL .02
Operator: 1402-86-85
Plotted: 21-Aug-86 10:40:43



Sample: A1 COMBUSTION
Size: 31.23 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 21-Aug-86 Time: 7:56:11
File: COAL/ANTH.08 COAL .02
Operator: 1402-86-85
Plotted: 21-Aug-86 11:49:58

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		39.0	61.8	0.70	2.25
OXIDATION		213.6		0.12	0.39
COMBUSTION	497.8	530.2	561.4	27.42	87.82
ASH	Residue at 771.6 °C			3.13	10.01

Modified Sample Weight: 31.23 mg

Sample: A1 COMBUSTION
Size: 31.23 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

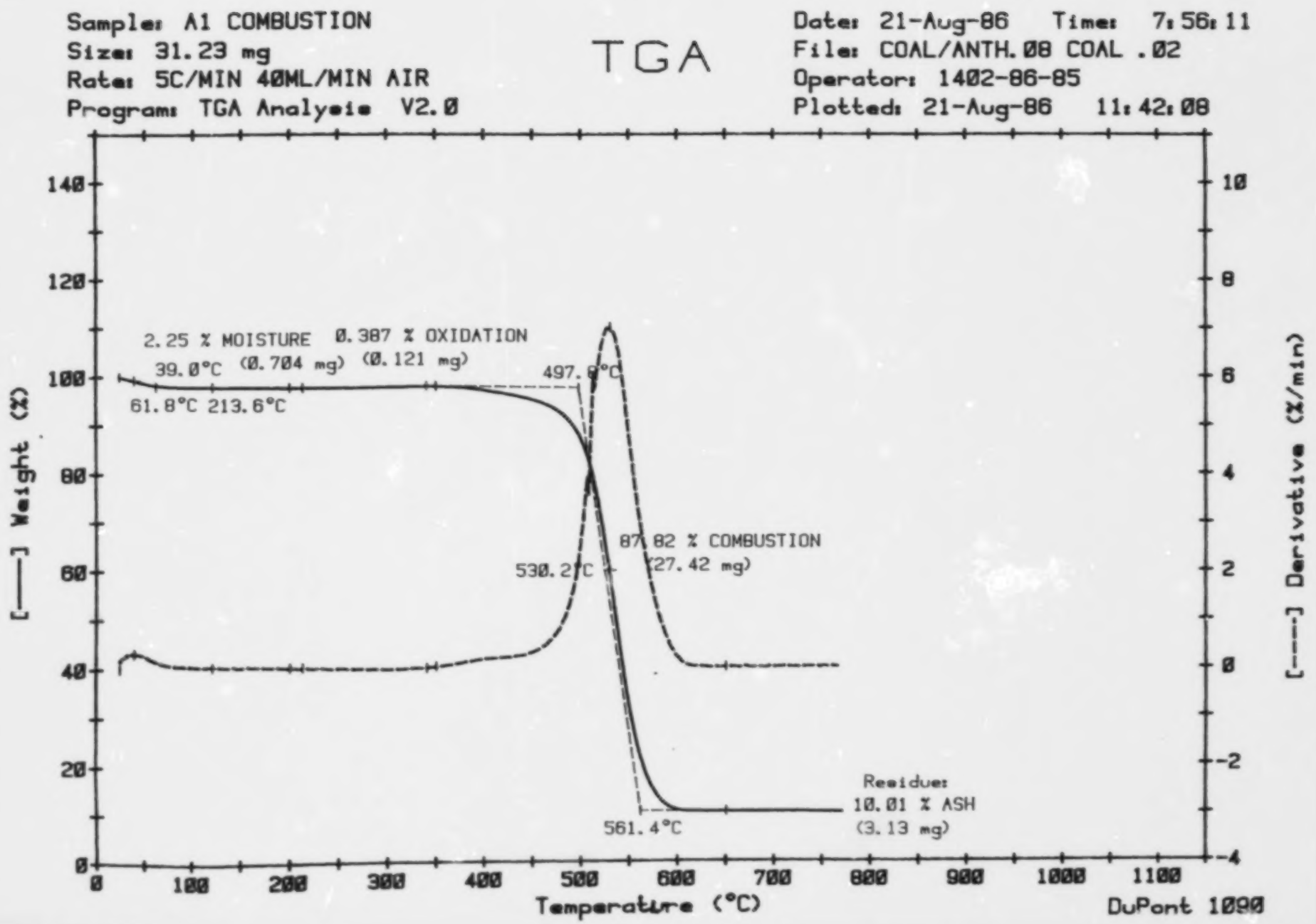
Date: 21-Aug-86 Time: 7:56:11
File: COAL/ANTH.08 COAL .02
Operator: 1402-86-85
Plotted: 11-Sep-86 15:45:51

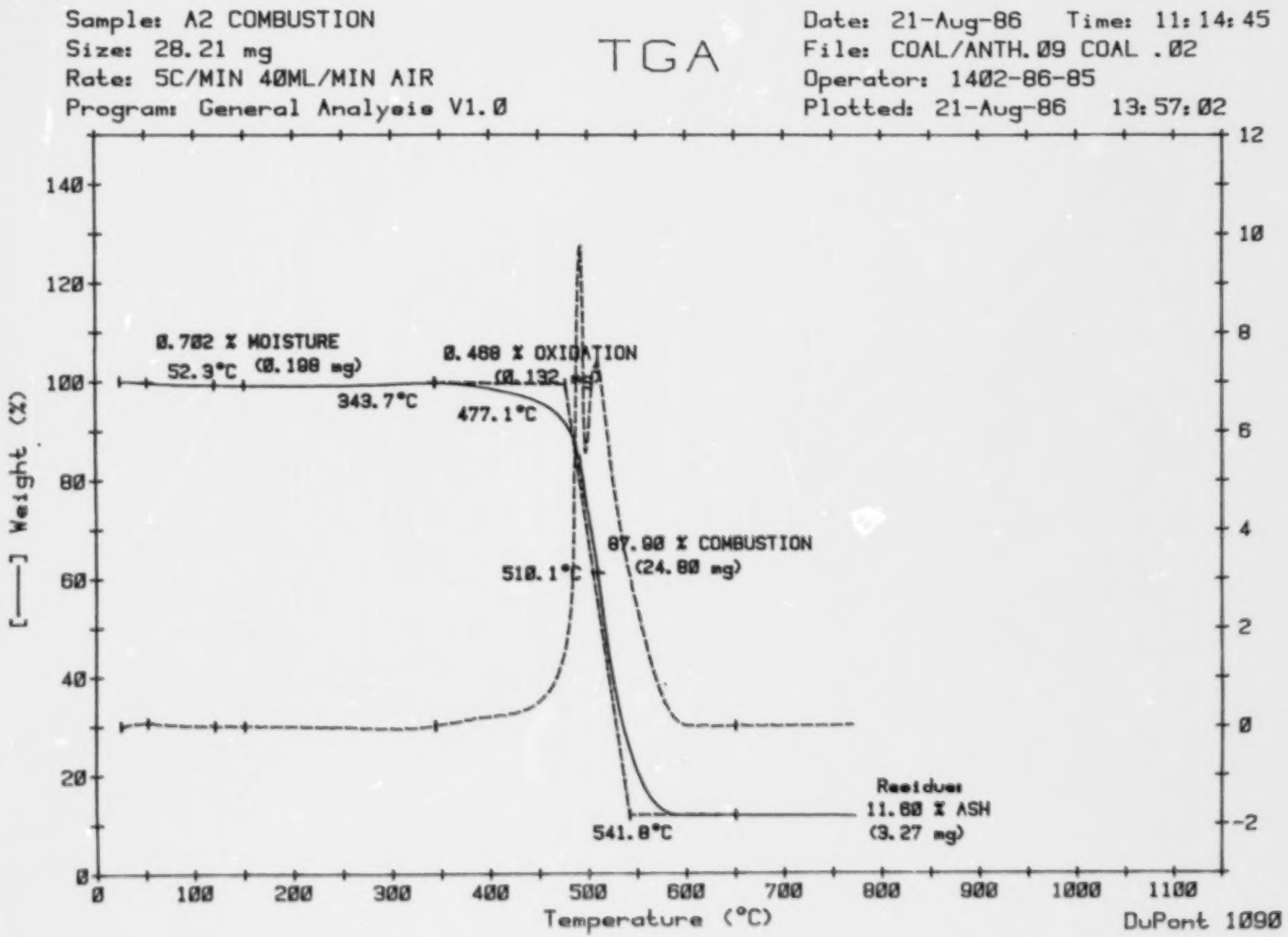
Temp [deg]	Sig-A [%]
400.4	97.179
405.2	97.031
410.5	96.852
415.3	96.686
420.1	96.516
425.5	96.311
430.3	96.128
435.0	95.930
440.3	95.699
445.2	95.485
450.0	95.209
455.3	94.989
460.0	94.548
465.3	94.114
470.1	93.643
475.4	93.012
480.3	92.330
485.2	91.475
490.2	90.377
495.2	88.955
500.5	87.018
505.3	84.632
510.4	81.638
515.6	77.167
520.4	72.210
525.4	66.132
530.2	59.849
535.1	52.906
540.1	45.595
545.3	38.371
550.2	32.155
555.3	26.935
560.2	22.882
565.4	19.227
570.2	16.723
575.1	14.747
580.1	13.245
585.1	12.140
590.0	11.348
595.1	10.837
600.2	10.523

517.7

537.1

517.5


Sample: A1 COMBUSTION
Size: 31.23 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0
TGA
Date: 21-Aug-86 Time: 7:56:11
File: COAL/ANTH.00 COAL .02
Operator: 1402-86-85
Plotted: 21-Aug-86 11:42:08
2.25 % MOISTURE 0.387 % OXIDATION
39.0°C (0.704 mg) (0.121 mg)
61.8°C 213.6°C
497.0°C
87.82 % COMBUSTION
530.2°C (27.42 mg)
561.4°C
Residue:
10.01 % ASH
(3.13 mg)
[——] Weight (%)
[---] Derivative (%/min)
Temperature (°C)
DuPont 1090


Sample: A2 COMBUSTION
Size: 28.21 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0
TGA
Date: 21-Aug-86 Time: 11:14:45
File: COAL/ANTH.09 COAL .02
Operator: 1402-86-85
Plotted: 21-Aug-86 13:57:02
0.702 % MOISTURE
52.3°C (0.198 mg)
343.7°C
0.488 % OXIDATION
(0.132 mg)
477.1°C
87.90 % COMBUSTION
(24.80 mg)
510.1°C
Residue
11.60 % ASH
(3.27 mg)
541.8°C
[——] Weight (%)
[- - -] Derivative (%/min)
Temperature (°C)
DuPont 1090

Sample: A2 COMBUSTION
Size: 28.21 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 21-Aug-86 Time: 11:14:45
File: COAL/ANTH.09 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 10:54:10

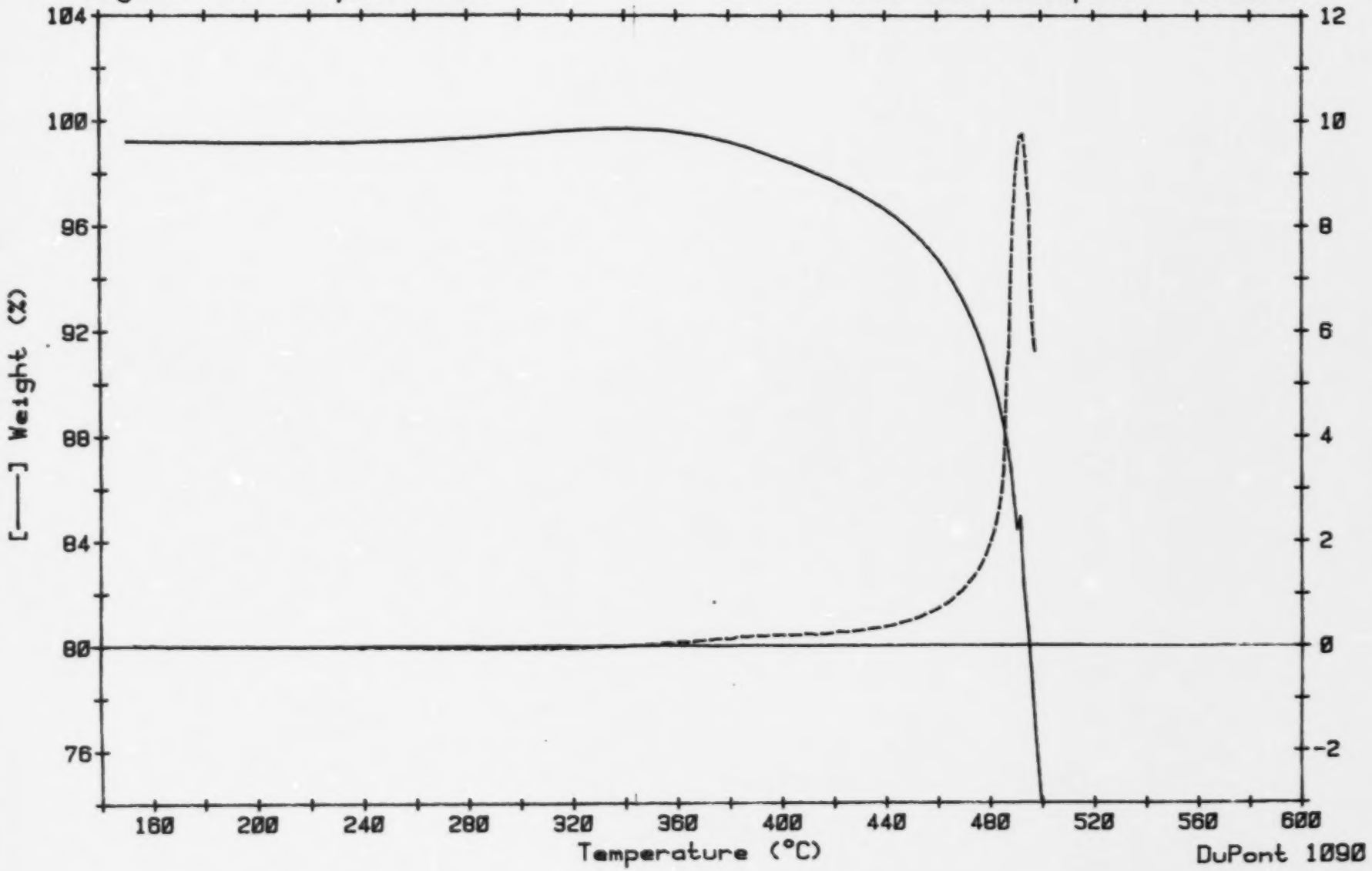
Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		52.3		0.20	0.70
OXIDATION		343.7		0.13	0.47
COMBUSTION	477.1	510.1	541.8	24.80	87.90
ASH	Residue at 772.8 °C			3.27	11.60

Modified Sample Weight: 28.21 mg

Sample: A2 COMBUSTION
Size: 28.21 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 21-Aug-86 Time: 11:14:45
File: COAL/ANTH.09 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 10:30:37



3.5

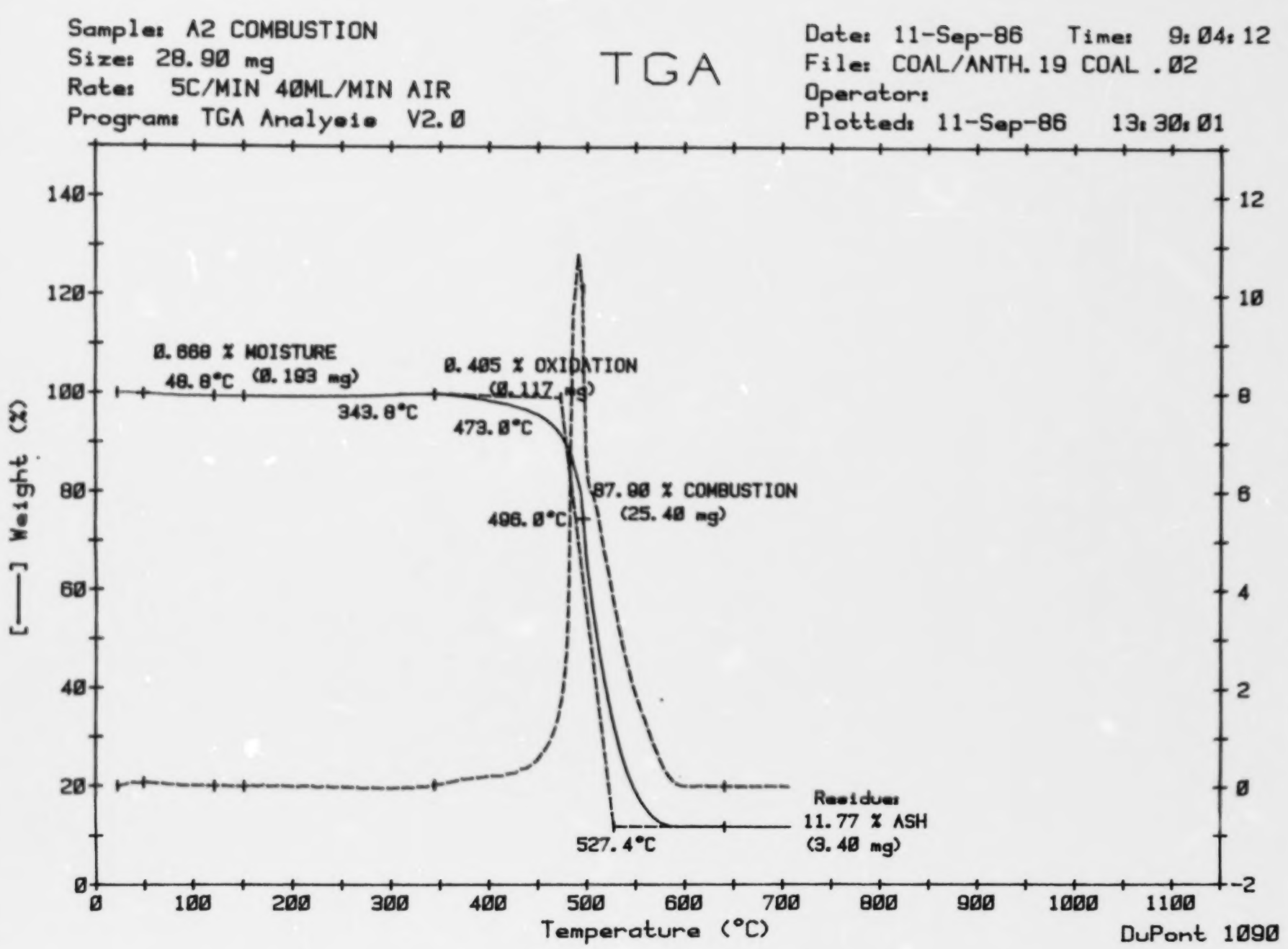
Sample: A2 COMBUSTION
Size: 28.21 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 21-Aug-86 Time: 11:14:45
File: COAL/ANTH.09 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 10:59:56

Temp [deg]	Sig-A [%]
500.0	73.521
505.2	67.633
510.1	61.822
515.2	53.192
520.1	48.230
525.4	39.672
530.4	34.515
535.4	30.849
540.2	26.529
545.4	23.179
550.2	20.581
555.3	18.184
560.4	16.231
565.3	14.852
570.0	13.803
575.2	12.967
580.0	12.467
585.2	12.118
590.1	11.958
595.0	11.875
600.3	11.850

$\frac{4.9}{6.962} \times 3.192 = 2.2$ 517.4

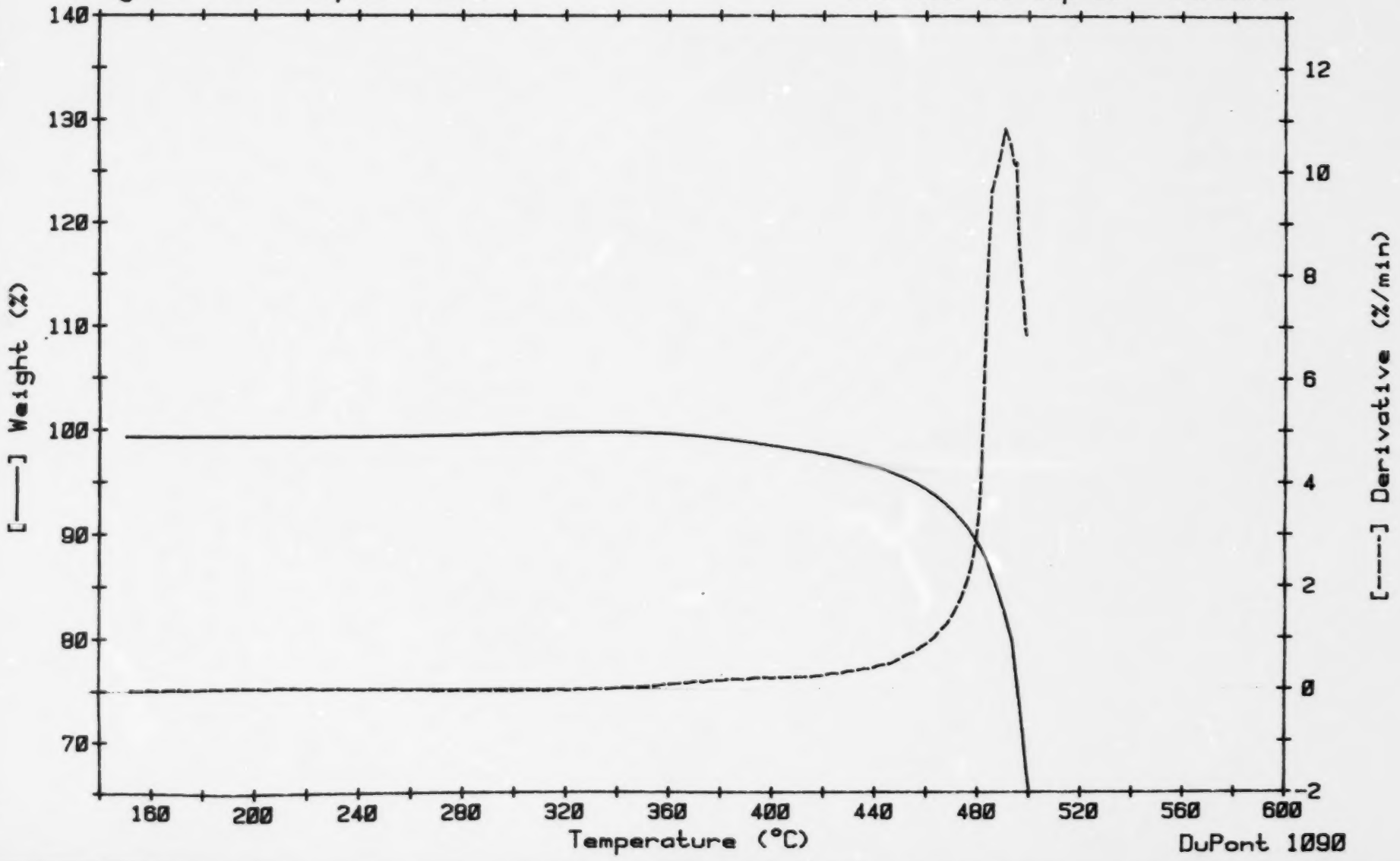
$\frac{5.2}{3.350} \times 1.529 = 2.4$ 540.7


Sample: A2 COMBUSTION
Size: 28.90 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0
TGA
Date: 11-Sep-86 Time: 9:04:12
File: COAL/ANTH.19 COAL .02
Operator:
Plotted: 11-Sep-86 13:30:01
0.668 % MOISTURE
48.8°C (0.193 mg)
343.8°C
0.405 % OXIDATION
(0.117 mg)
473.8°C
87.90 % COMBUSTION
(25.40 mg)
496.8°C
Residue:
11.77 % ASH
(3.40 mg)
527.4°C
[——] Weight (%)
[----] Derivative (%/min)
Temperature (°C)
DuPont 1090

Sample: A2 COMBUSTION
Size: 28.90 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 11-Sep-86 Time: 9:04:12
File: COAL/ANTH.19 COAL .02
Operator:
Plotted: 11-Sep-86 11:28:05



DuPont 1090

Sample: A2 COMBUSTION
Size: 28.90 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 11-Sep-86 Time: 9:04:12
File: COAL/ANTH.19 COAL .02
Operator:
Plotted: 11-Sep-86 13:46:22

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		48.8		0.19	0.67
OXIDATION		343.8		0.12	0.40
COMBUSTION	473.0	496.0	527.4	25.40	87.90
ASH	Residue at 711.1 °C			3.40	11.77

Modified Sample Weight: 28.90 mg

Sample: A2 COMBUSTION
Size: 28.90 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

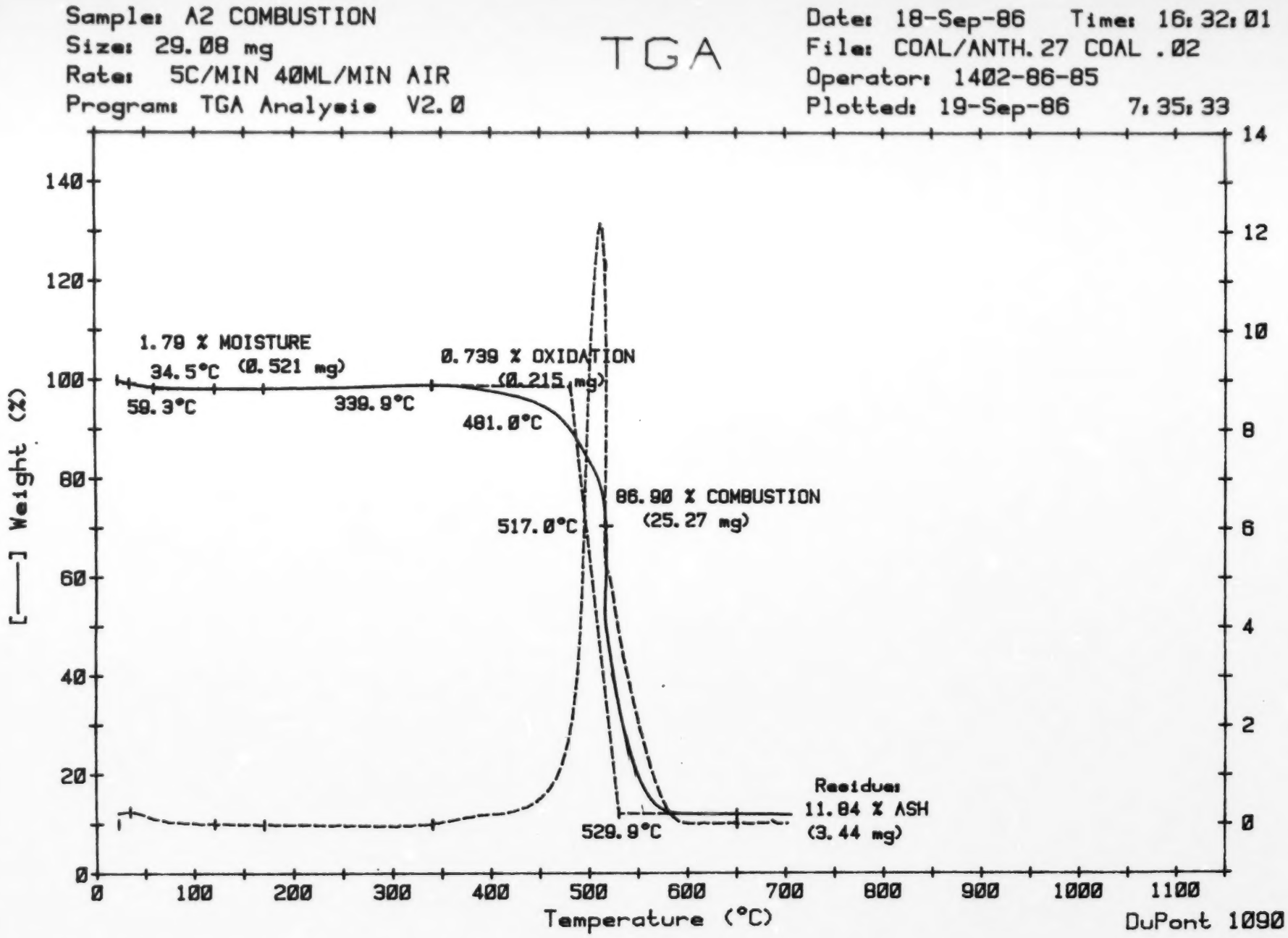
Date: 11-Sep-86 Time: 9:04:12
File: COAL/ANTH.19 COAL .02
Operator:
Plotted: 11-Sep-86 15:51:38

Temp [deg]	Sig-A [%]
480.1	89.015
485.5	86.029
490.8	82.119
495.2	76.095
500.3	64.819
505.3	56.927
510.2	50.550
515.4	44.166
520.4	38.935
525.3	34.254
530.1	30.164
535.3	26.313
540.3	23.289
545.3	20.729
550.4	18.545
555.2	16.867
560.1	15.456
565.3	14.210
570.1	13.359
575.1	12.670
580.2	12.234

75 $\frac{5.1}{11.276} \times 1.095 = \frac{0.49}{495.2}$ → 496

50 $\frac{5.2}{6.384} \times 0.55 = \frac{0.45}{510.2}$ → 511

25 $\frac{5}{3.018} \times 1.313 = \frac{2.1}{535.3}$ → 537


Sample: A2 COMBUSTION
Size: 29.08 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0
TGA
Date: 18-Sep-86 Time: 16:32:01
File: COAL/ANTH.27 COAL .02
Operator: 1402-86-85
Plotted: 19-Sep-86 7:35:33
1.79 % MOISTURE
34.5°C (0.521 mg)
59.3°C
0.739 % OXIDATION
(0.215 mg)
339.9°C
481.0°C
86.90 % COMBUSTION
(25.27 mg)
517.0°C
Residue:
11.84 % ASH
(3.44 mg)
529.9°C
[——] Weight (%)
[---] Derivative (%/min)
Temperature (°C)
DuPont 1090

Sample: A2 COMBUSTION
Size: 29.08 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 18-Sep-86 Time: 16:32:01
File: COAL/ANTH.27 COAL .02
Operator: 1402-86-85
Plotted: 19-Sep-86 7:59:41

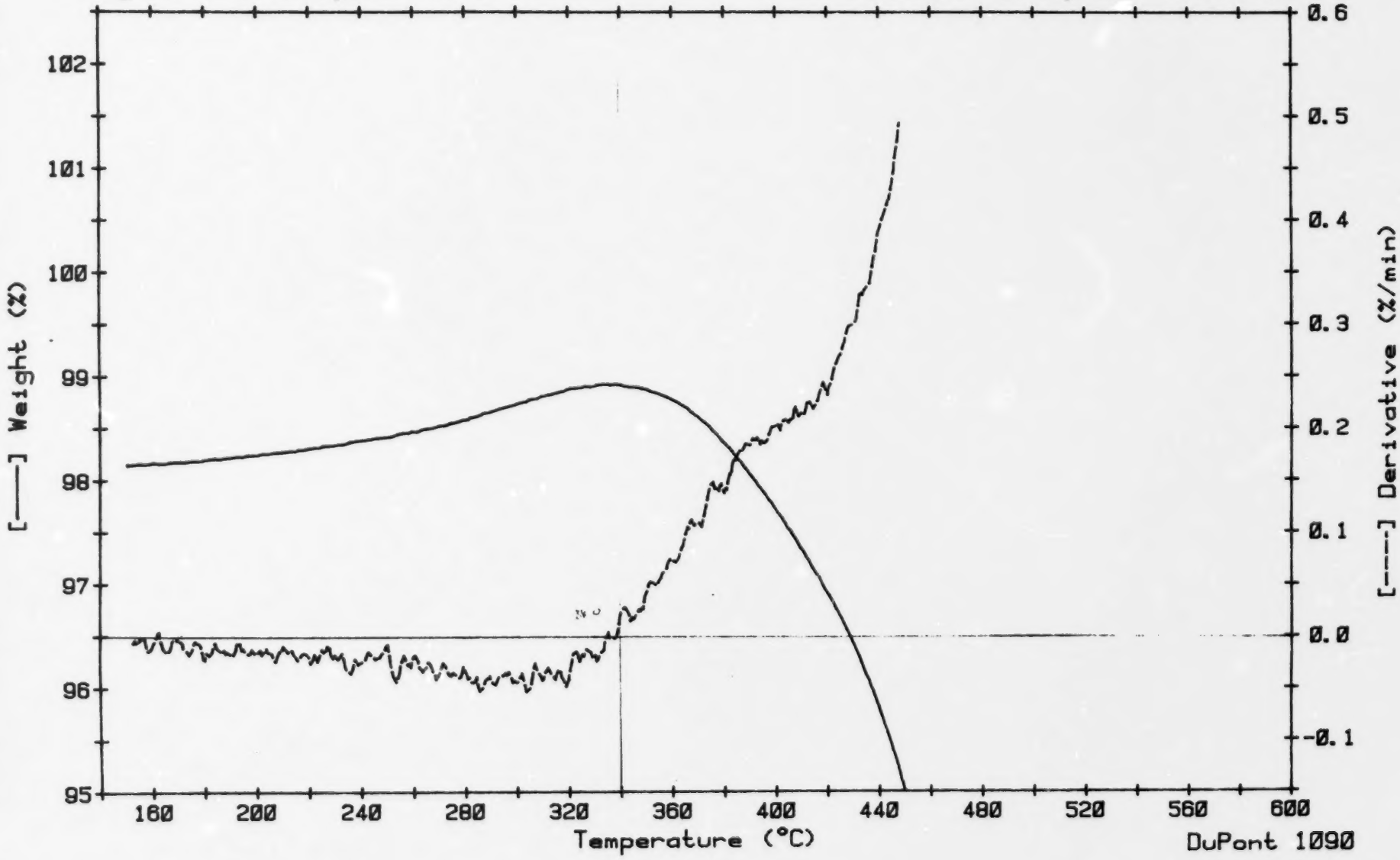
Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		34.5	59.3	0.52	1.79
OXIDATION		339.9		0.21	0.74
COMBUSTION	481.0	517.0	529.9	25.27	86.90
ASH	Residue at 708.3 °C			3.44	11.84

Modified Sample Weight: 29.08 mg

Sample: A2 COMBUSTION
Size: 29.08 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 18-Sep-86 Time: 16:32:01
File: COAL/ANTH.27 COAL .02
Operator: 1402-86-85
Plotted: 19-Sep-86 7:42:50



3.16

Sample: A2 COMBUSTION
Size: 29.08 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 18-Sep-86 Time: 16:32:01
File: COAL/ANTH.27 COAL .02
Operator: 1402-86-85
Plotted: 19-Sep-86 8:07:44

Temp [deg]	Sig-A [%]
440.3	95.774
445.2	95.403
450.2	94.970
455.4	94.457
460.1	93.921
465.3	93.185
470.0	92.387
475.5	91.249
480.2	90.100
485.4	88.602
491.0	86.762
496.5	84.847
501.0	83.298
506.9	81.020
511.6	78.499
515.3	74.851

3.7 × 3.498 / 3.698 = 515

Temp [deg]	Sig-A [%]
520.2	45.776
525.0	39.497
530.3	33.631
535.4	28.958
540.4	25.248
545.4	22.064
550.0	19.585
555.3	17.364
560.0	15.748
565.3	14.376
570.3	13.465
575.4	12.848
580.4	12.457
585.4	12.241
590.5	12.134
595.3	12.096
600.1	12.090

Sample: C COMBUSTION
Size: 29.78 mg
Rate: 5C/MIN AIR 40ML/MIN
Program: General Analysis V1.0

Date: 14-Aug-86 Time: 12:06:55
File: COAL/ANTH.03 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 13:56:33

Temp [deg]	Sig-A [%]
350.0	87.891
355.1	86.843
360.1	85.691
365.0	84.429
370.1	83.015
375.2	81.443
380.4	79.714
385.0	77.783
390.5	75.100
395.3	72.239
400.1	68.828
405.7	63.498
410.0	58.110
415.2	47.550
420.0	35.189

Temp [deg]	Sig-A [%]
425.3	28.990
430.2	25.901
435.3	23.184
440.0	20.985
445.2	18.943
450.1	17.391
455.2	15.988
460.5	14.890
465.0	14.198
470.0	13.820
475.1	13.201
480.0	12.898
485.0	12.680
490.1	12.536
495.1	12.435
500.2	12.384

Sample: C COMBUSTION
Size: 29.78 mg
Rate: 5C/MIN AIR 40ML/MIN
Program: TGA Analysis V2.0

Date: 14-Aug-86 Time: 12:06:55
File: COAL/ANTH.03 COAL .02
Operator: 1402-86-85
Plotted: 14-Aug-86 15:47:06

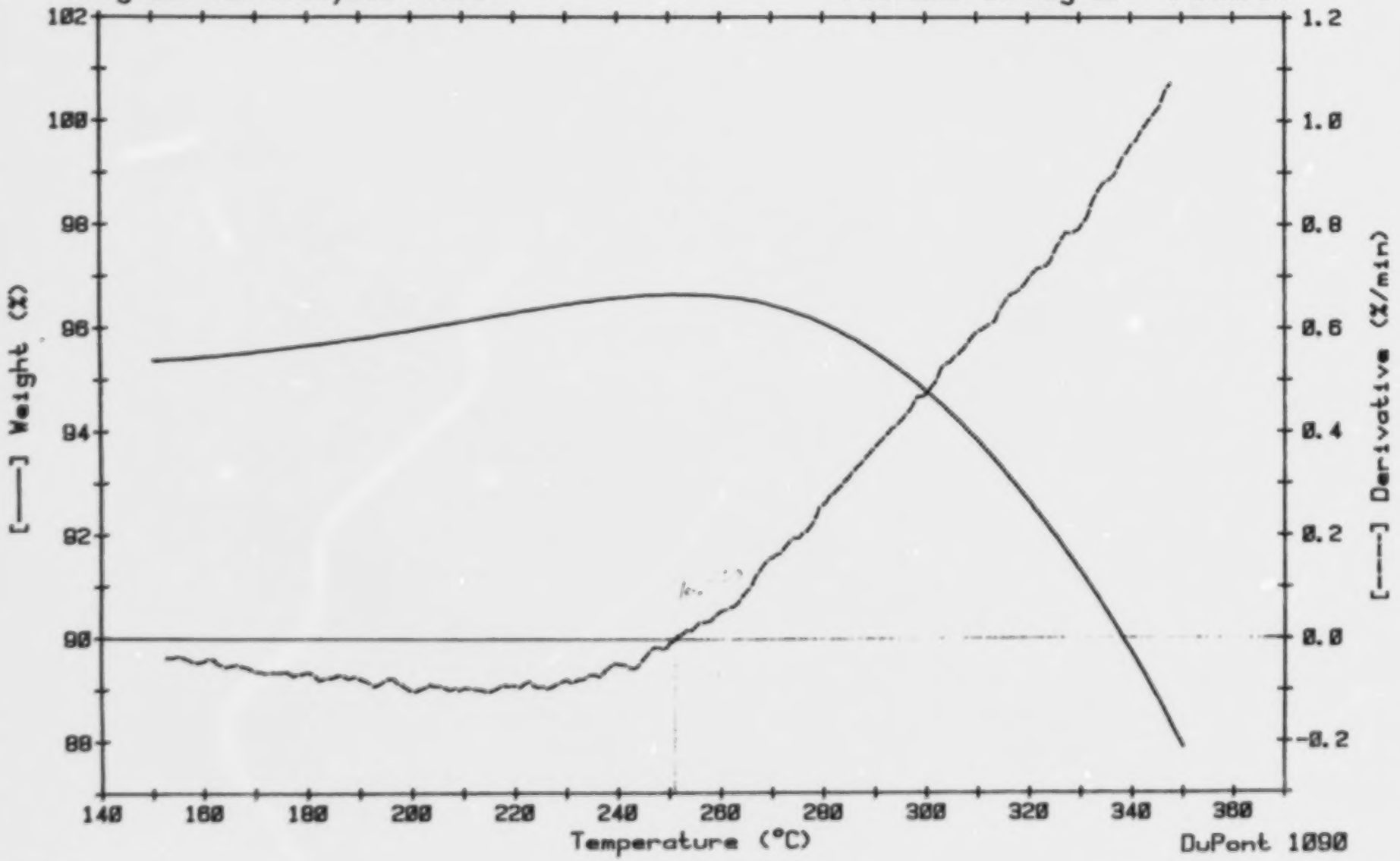
Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		56.8	81.8	1.38	4.63
OXIDATION		259.9		0.38	1.27
COMBUSTION	381.5	411.4	425.2	25.12	84.36
ASH	Residue at 701.1 °C			3.51	11.80

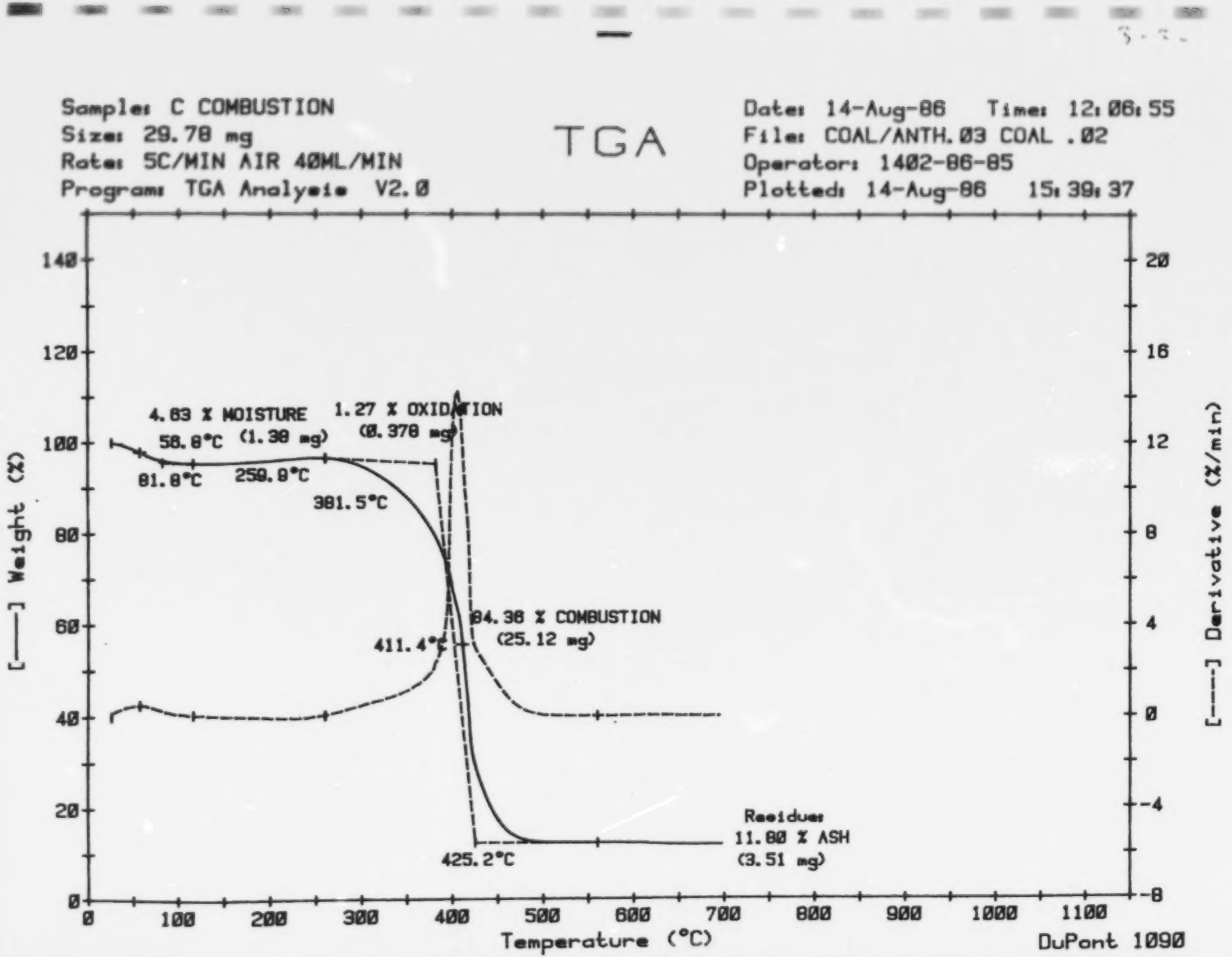
Modified Sample Weight: 29.78 mg

Sample: C COMBUSTION
Size: 29.78 mg
Rate: 5C/MIN AIR 40ML/MIN
Program: TGA Analysis V2.0

TGA

Date: 14-Aug-86 Time: 12:06:55
File: COAL/ANTH.03 COAL .02
Operator: 1402-86-85
Plotted: 14-Aug-86 14:58:14




Sample: C COMBUSTION
Size: 29.78 mg
Rate: 5C/MIN AIR 40ML/MIN
Program: TGA Analysis V2.0
TGA
Date: 14-Aug-86 Time: 12:06:55
File: COAL/ANTH.03 COAL .02
Operator: 1402-86-85
Plotted: 14-Aug-86 15:39:37
4.63 % MOISTURE
58.8°C (1.38 mg)
1.27 % OXIDATION
(0.378 mg)
81.8°C
259.8°C
381.5°C
84.38 % COMBUSTION
(25.12 mg)
411.4°C
Residue
11.80 % ASH
(3.51 mg)
425.2°C
[——] Weight (%)
[- - -] Derivative (%/min)
Temperature (°C)
DuPont 1090

Sample: G COMBUSTION
Size: 30.59 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

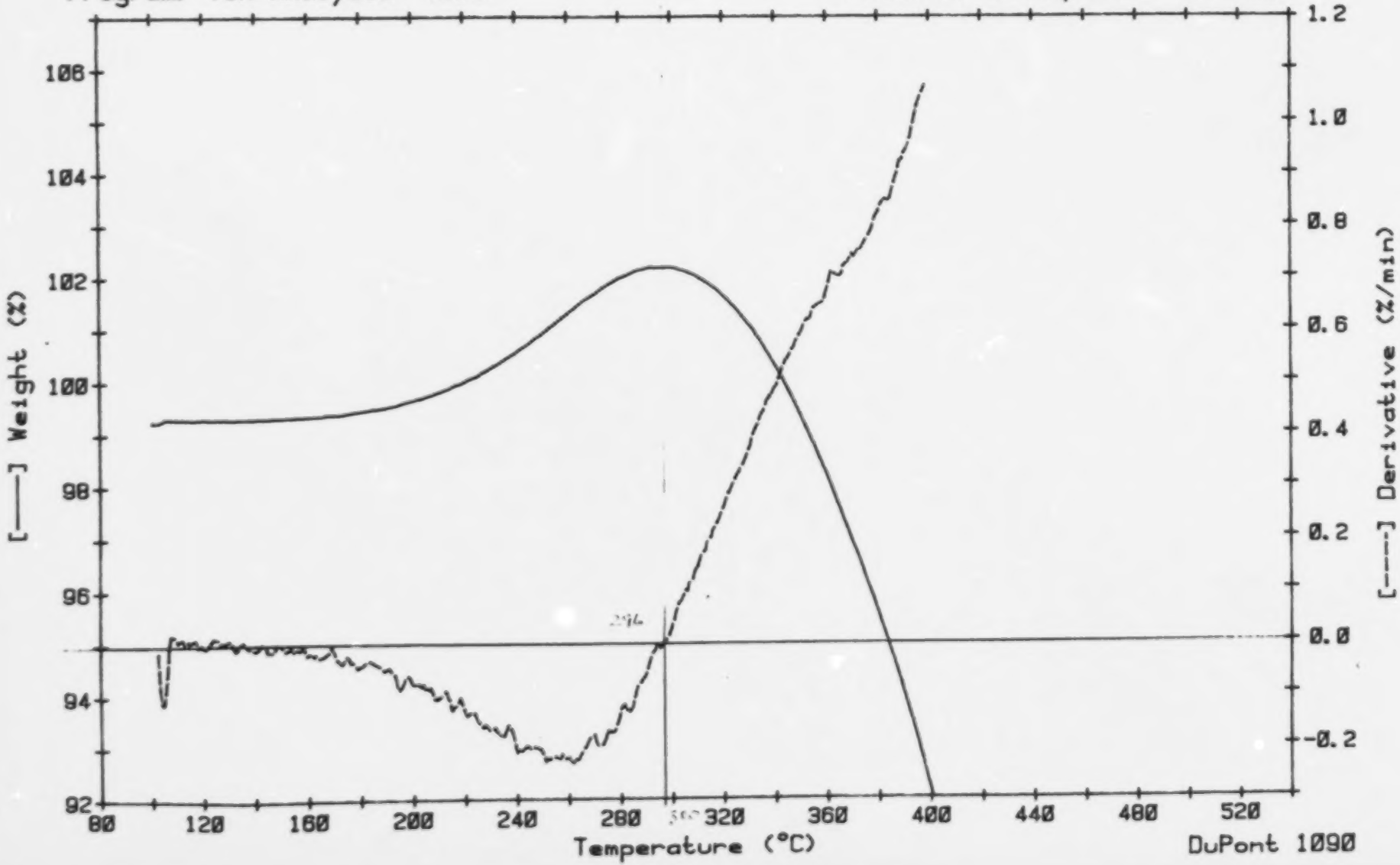
Date: 11-Sep-86 Time: 19:28:11
File: COAL/ANTH.21 COAL .02
Operator: 1402-86-85
Plotted: 15-Sep-86 9:50:20

Temp [deg]	Sig-A [%]			
440.0	78.258	> 75	$\frac{5.1}{3.606} \times 3.258 = \frac{4.6}{440}$	445
445.1	74.852			
450.3	70.300			
455.2	64.930			
460.0	57.878			
465.0	52.737	> 50	$\frac{5.2}{4.519} \times 2.737 = \frac{3.2}{465}$	467
470.2	48.218			
475.2	43.842			
480.2	39.986			
485.0	36.477			
490.0	33.123			
495.1	30.082			
500.0	27.323	> 25	$\frac{5.0}{2.442} \times 2.323 = \frac{4.8}{500}$	506
505.0	24.881			
510.0	22.693			
515.1	20.787			
520.1	19.117			
525.0	17.671			
530.0	16.485			
535.0	15.485			
540.1	14.647			
545.1	14.048			
550.0	13.555			
555.1	13.212			
560.1	12.954			

Sample: G COMBUSTION
Size: 30.59 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 11-Sep-86 Time: 19:28:11
File: COAL/ANTH.21 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 8:20:09



Sample: G COMBUSTION
Size: 30.59 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 11-Sep-86 Time: 19:28:11
File: COAL/ANTH.21 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 8:59:32

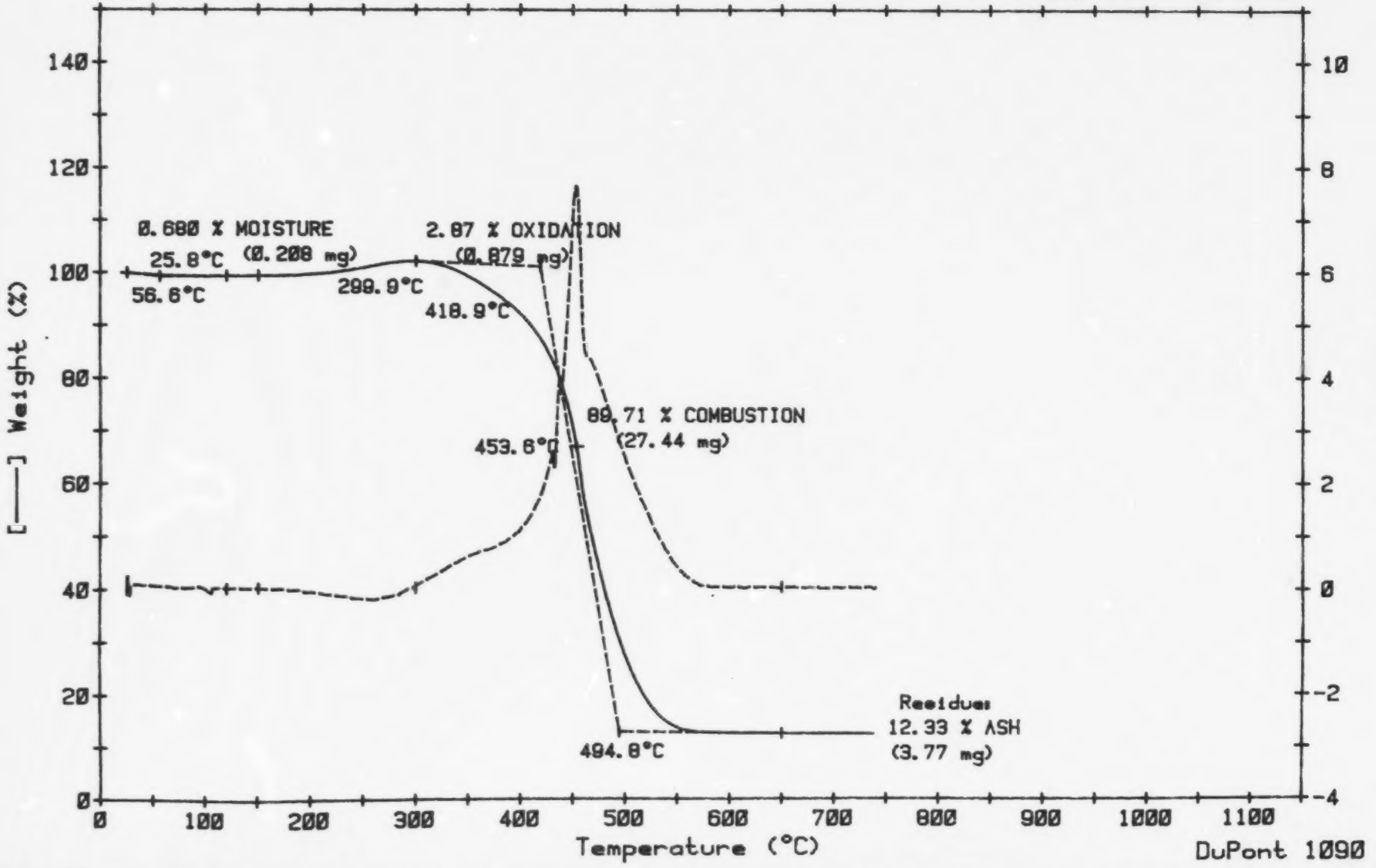
Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		25.8	56.6	0.21	0.68
OXIDATION		299.9		0.88	2.87
COMBUSTION	418.9	453.6	494.8	27.44	89.71
ASH	Residue at 741.9 °C			3.77	12.33

Modified Sample Weight: 30.59 mg

Sample: G COMBUSTION
Size: 30.59 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 11-Sep-86 Time: 19:28:11
File: COAL/ANTH.21 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 8:54:49



DuPont 1090

3.25

Sample: G COMBUSTION
Size: 30.54 mg
Rate: 5C/MIN AIR 40ML/MIN
Program: General Analysis V1.0

Date: 14-Aug-86 Time: 14:43:08
File: COAL/ANTH.04 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 10:05:35

Temp [deg]	Sig-A [%]
400.5	91.913
405.4	90.914
410.3	89.804
415.2	88.560
420.1	87.142
425.2	85.515
430.2	83.583
435.5	81.215
~~440.4~~	78.458
445.2	75.230
450.0	71.255
455.2	63.544
460.3	58.466
465.0	54.448
470.1	49.956

Temp [deg]	Sig-A [%]
475.0	45.644
480.2	41.220
485.4	37.153
490.2	33.781
495.3	30.431
500.1	27.700
505.2	25.019
510.3	22.681
515.1	20.811
520.2	18.037
525.4	17.501
530.2	16.332
535.4	15.258
540.2	14.479
545.0	13.847
550.3	13.328

505.2

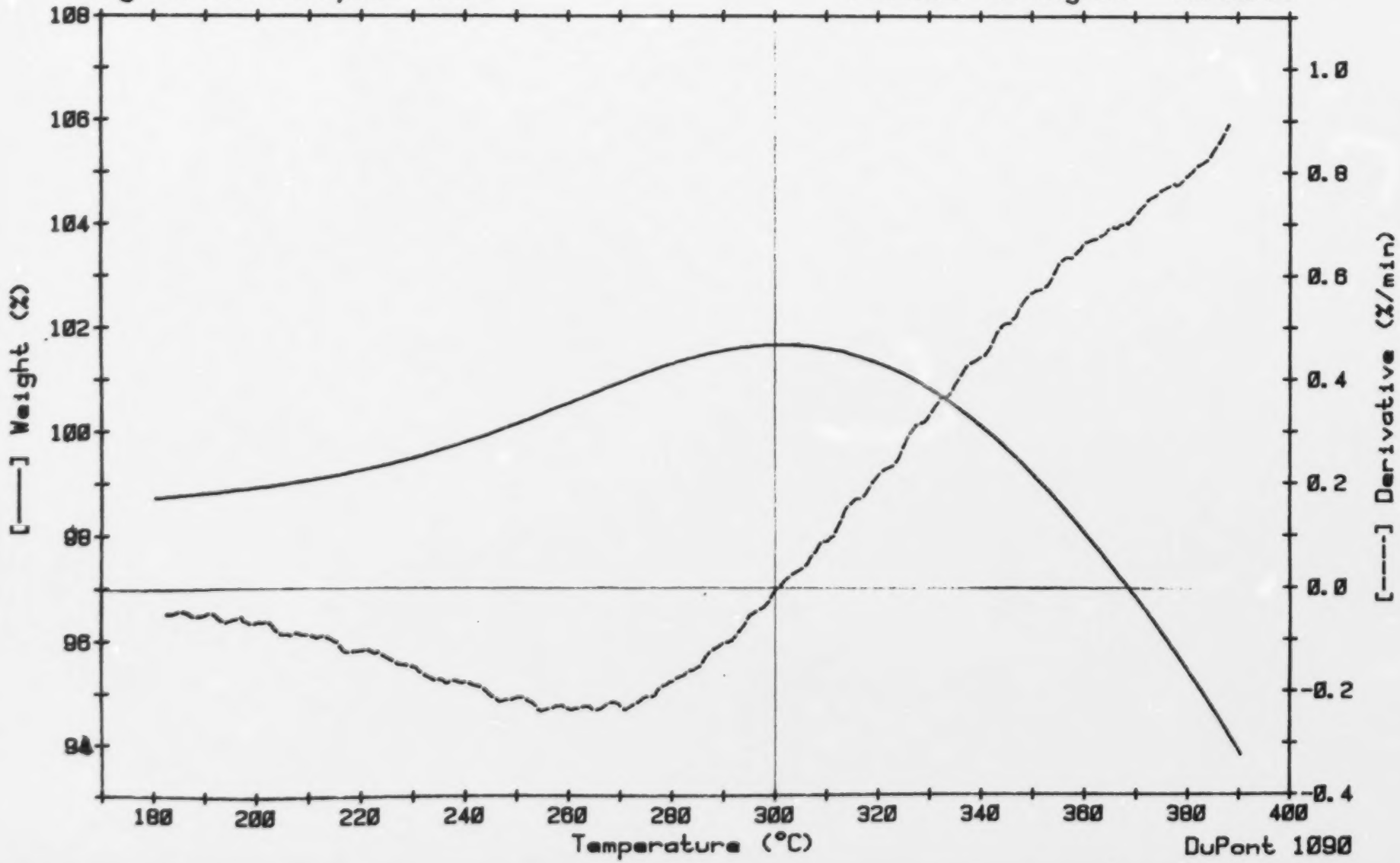
75 $\frac{4.8}{3.975} \times 0.23 = \frac{445.2}{446}$

50 $\frac{5.1}{4.482} \times 4.448 = 470.$

Sample: G COMBUSTION
Size: 30.54 mg
Rate: 5C/MIN AIR 40ML/MIN
Program: TGA Analysis V2.0

TGA

Date: 14-Aug-86 Time: 14:43:08
File: COAL/ANTH.04 COAL .02
Operator: 1402-86-85
Plotted: 20-Aug-86 12:43:11



DuPont 1090

Sample: G COMBUSTION
Size: 30.54 mg
Rate: 5C/MIN AIR 40ML/MIN
Program: TGA Analysis V2.0

Date: 14-Aug-86 Time: 14:43:08
File: COAL/ANTH.04 COAL .02
Operator: 1402-86-85
Plotted: 21-Aug-86 12:41:30

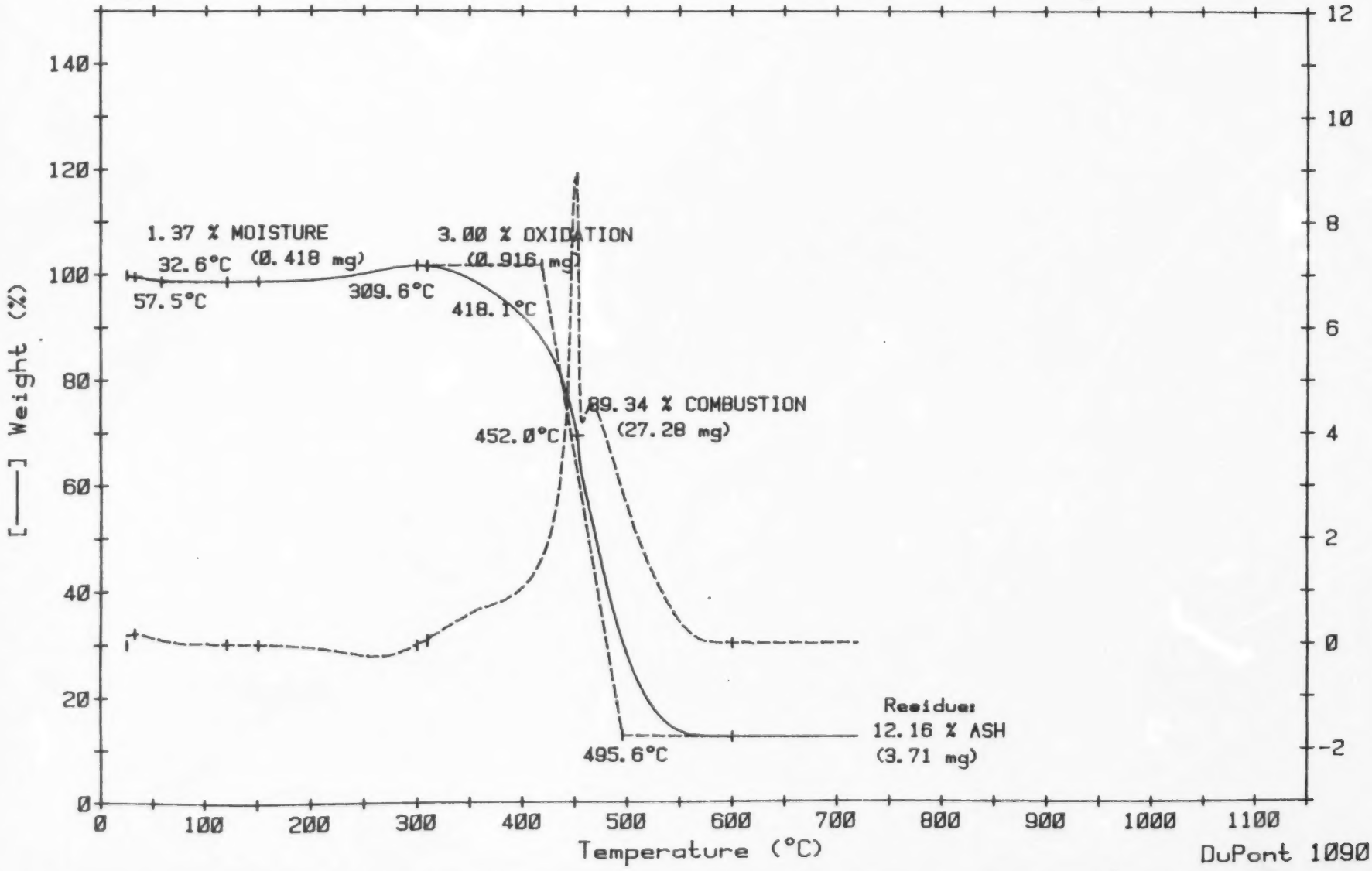
Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		32.6	57.5	0.42	1.37
OXIDATION		309.6		0.92	3.00
COMBUSTION	418.1	452.0	495.6	27.28	89.34
ASH	Residue at 723.7 °C			3.71	12.16

Modified Sample Weight: 30.54 mg

Sample: G COMBUSTION
Size: 30.54 mg
Rate: 5C/MIN AIR 40ML/MIN
Program: TGA Analysis V2.0

TGA

Date: 14-Aug-86 Time: 14:43:08
File: COAL/ANTH.04 COAL .02
Operator: 1402-86-85
Plotted: 21-Aug-86 12:06:16



DuPont 1090

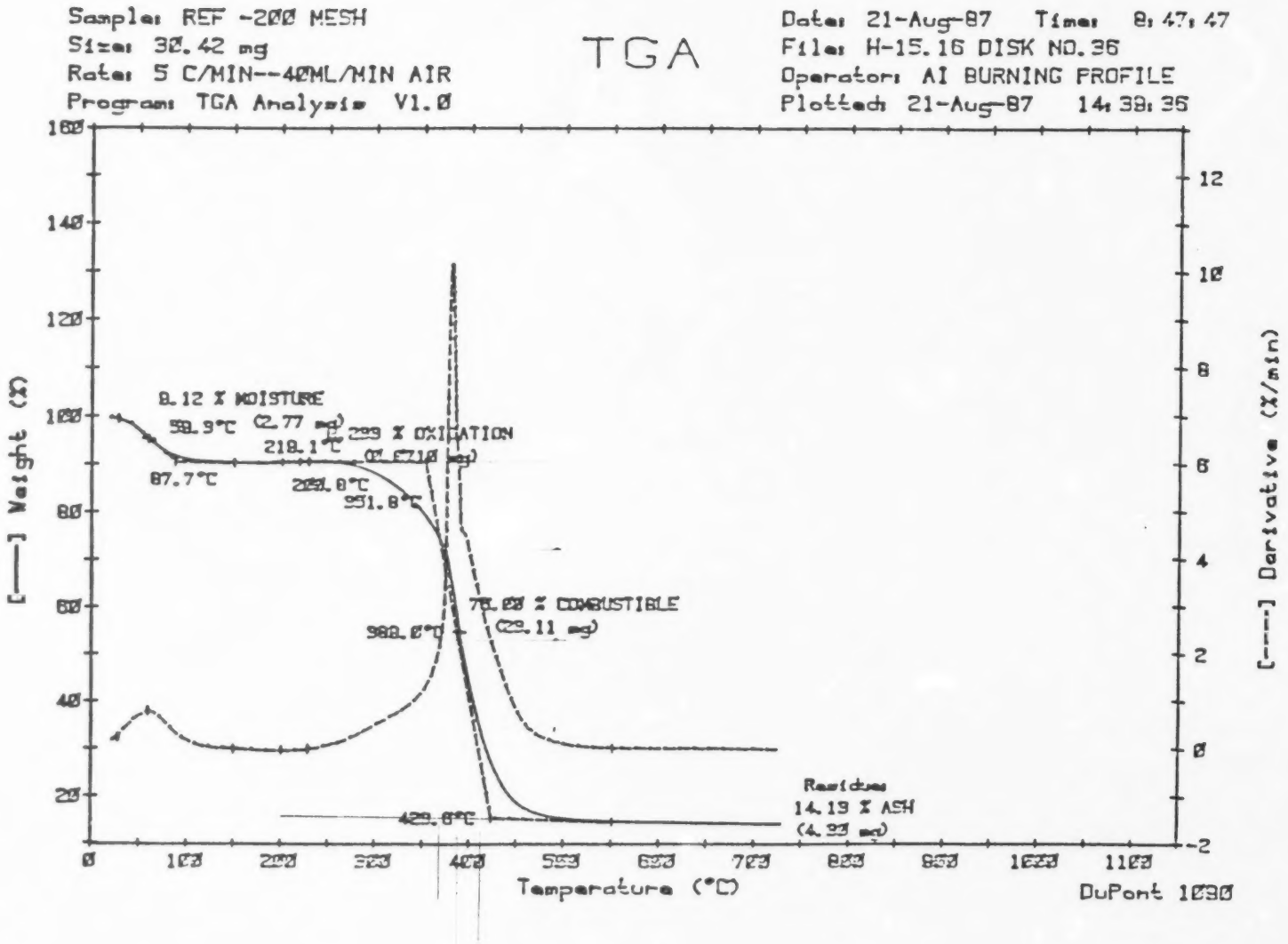


Figure 3.9 TGA Combustion Profile for Sample 0

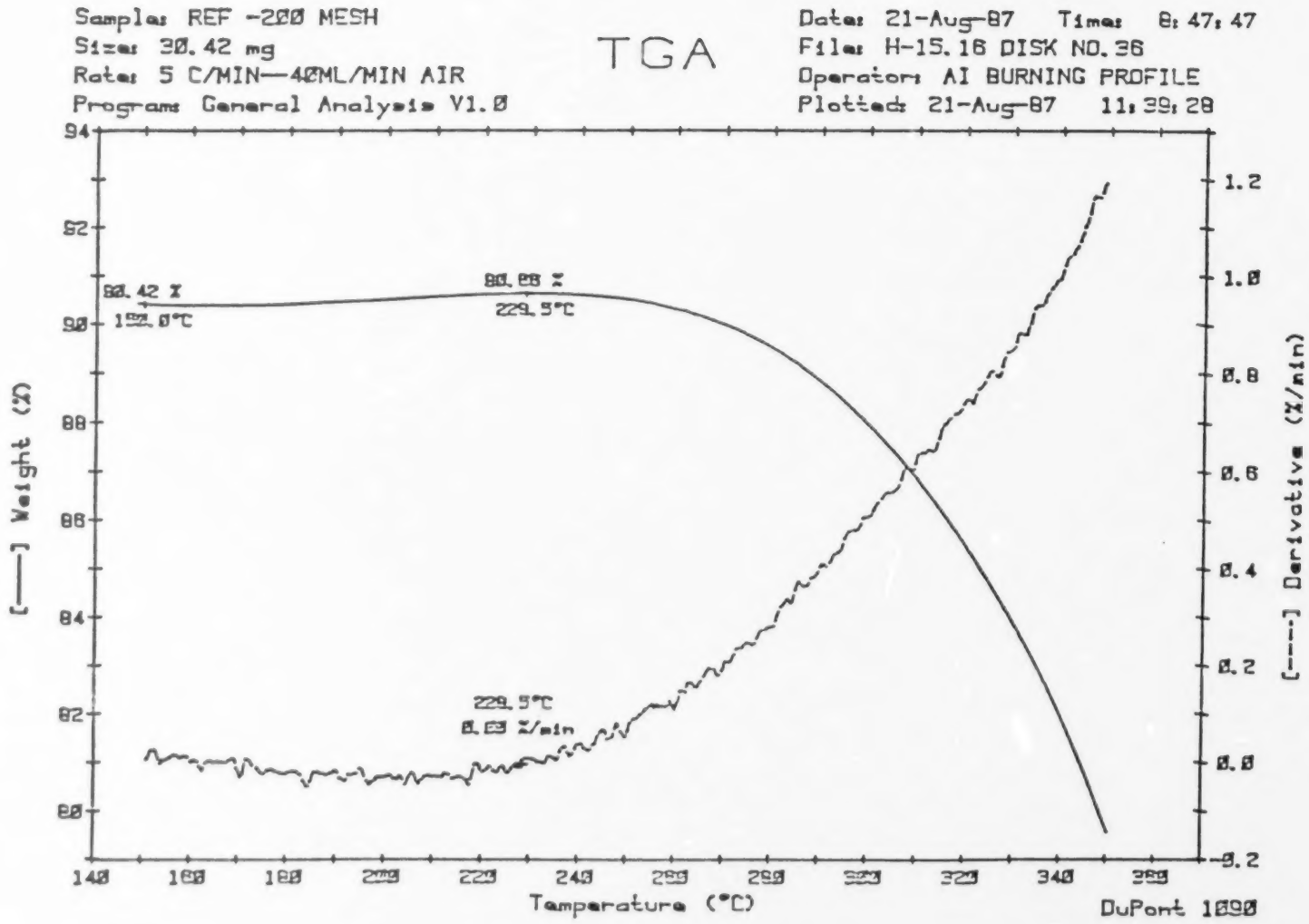


Figure 3.10 TGA Ignition Temperature for Sample 0

Sample: REF -200 MESH
Size: 30.42 mg
Rate: 5 C/MIN--40ML/MIN AIR
Program: TGA Analysis V1.0

Date: 21-Aug-87 Time: 8:47:47
File: H-15.16 DISK NO.36
Operator: AI BURNING PROFILE
Plotted: 21-Aug-87 15:05:45

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		58.3	87.7	2.77	8.12
OXIDATION		200.8	218.1	(0.07)	(0.23)
COMBUSTIBLE	351.8	388.0	423.6	23.11	76.00
ASH	Residue at 732.8 °C			4.30	14.13

Modified Sample Weight: 30.41 mg

Figure 3.11 TGA Combustion Profile Temperatures for Sample 0

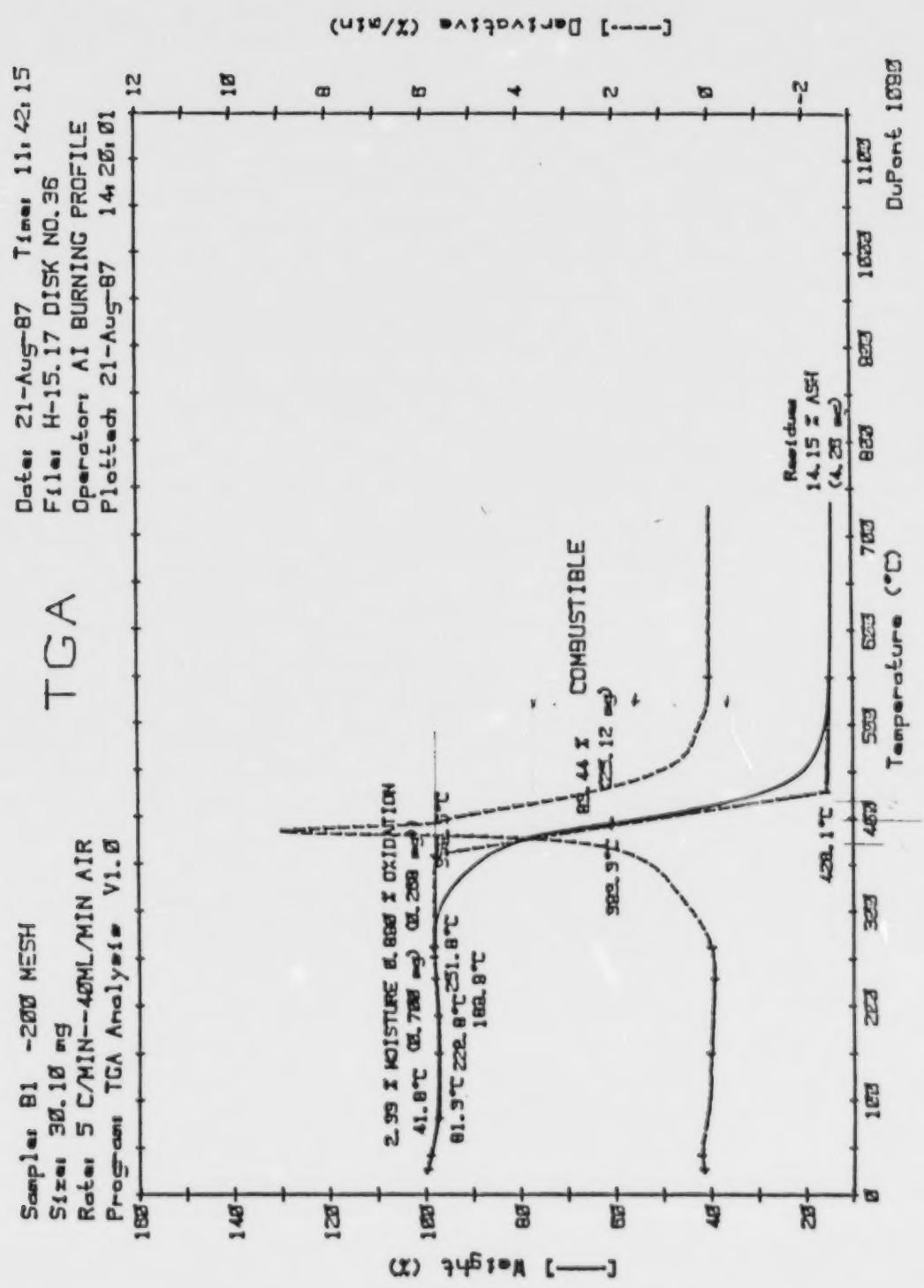


Figure 3.15 TGA Combustion Profile for Sample B1

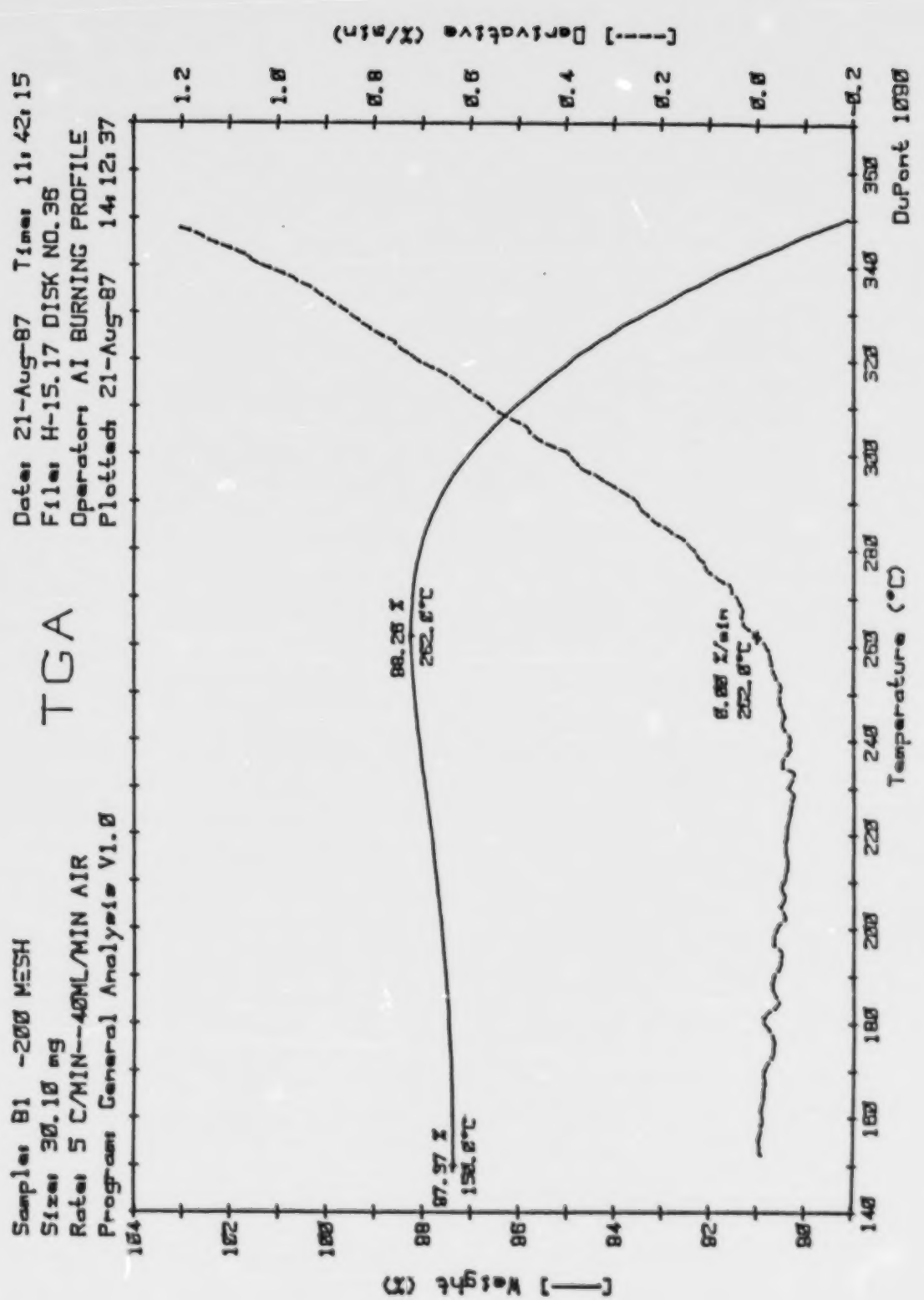


Figure 3.16 TGA Ignition Temperature for Sample B1

Sample: B1 -200 MESH
Size: 30.10 mg
Rate: 5 C/MIN--40ML/MIN AIR
Program: TGA Analysis V1.0

Date: 21-Aug-87 Time: 11:42:15
File: H-15.17 DISK NO.36
Operator: AI BURNING PROFILE
Plotted: 21-Aug-87 14:31:34

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		41.8	81.3	0.70	2.33
OXIDATION	189.9	228.8	251.8	(0.27)	(0.89)
COMBUSTIBLE	359.5	383.3	428.1	25.12	83.44
ASH	Residue at 736.7 °C			4.26	14.15

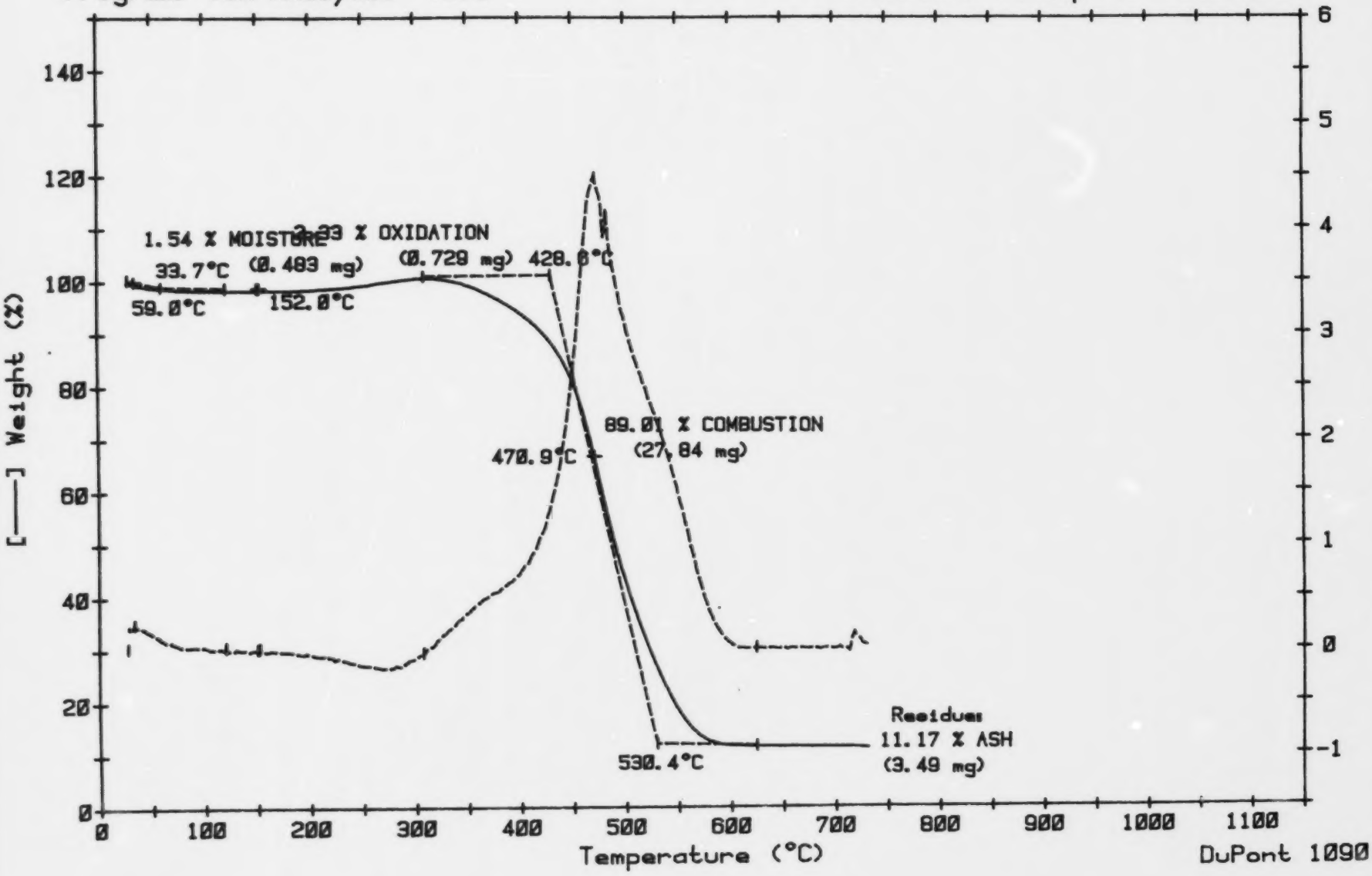
Modified Sample Weight: 30.10 mg

Figure 3.17 TGA Combustion Profile Temperatures for Sample B1

Sample: 25%A1+75%G COMB.
Size: 31.28 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analyeie V2.0

TGA

Date: 26-Aug-86 Time: 14:06:11
File: COAL/ANTH.15 COAL .02
Operator: 1402-86-85
Plotted: 10-Sep-86 10:20:14



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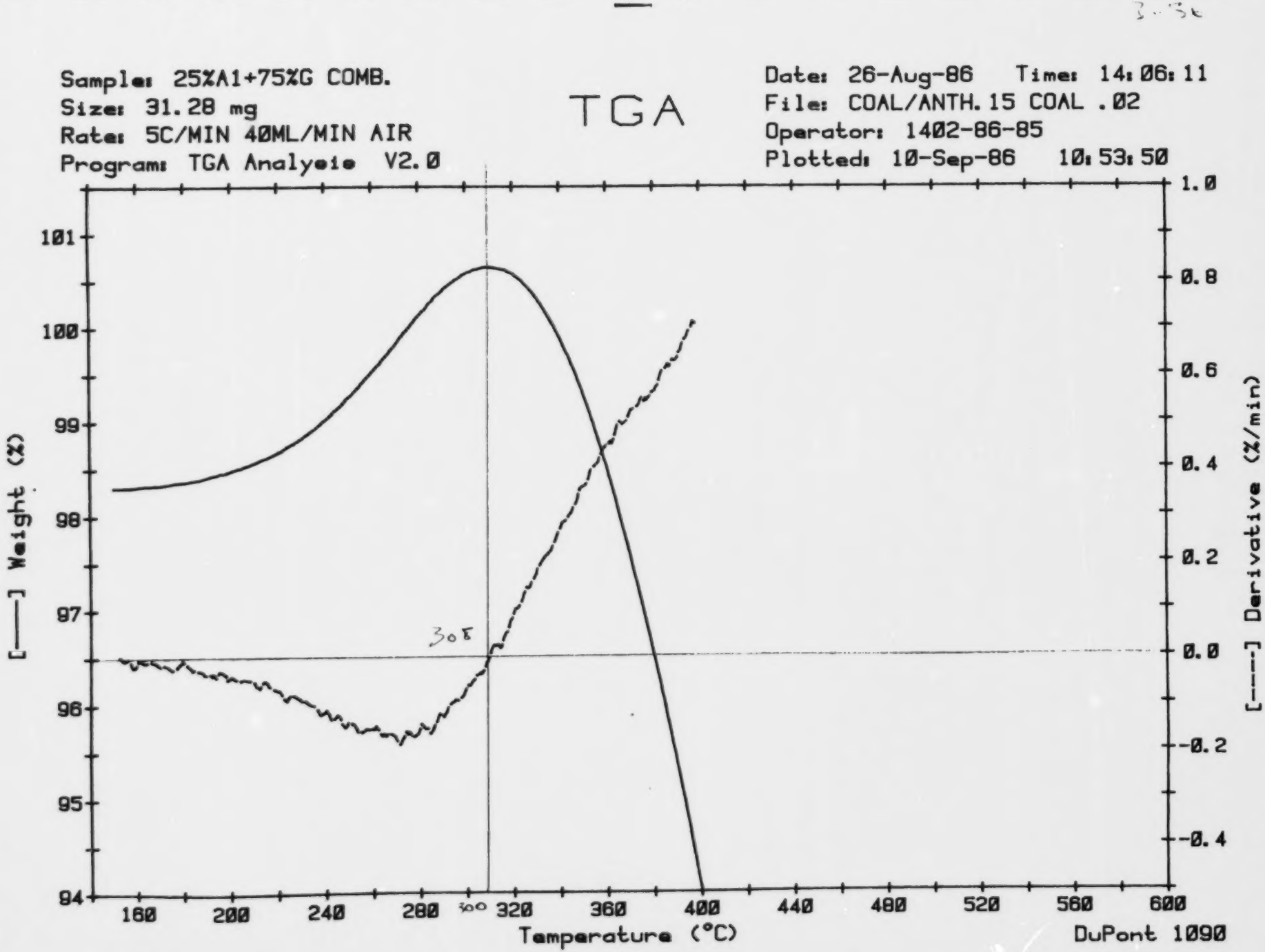

Sample: 25%A1+75%G COMB.
Size: 31.28 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0
TGA
Date: 26-Aug-86 Time: 14:06:11
File: COAL/ANTH.15 COAL .02
Operator: 1402-86-85
Plotted: 10-Sep-86 10:53:50
[——] Weight (%)
[----] Derivative (%/min)
Temperature (°C)
DuPont 1090
101
100
99
98
97
96
95
94
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
160
200
240
280
300
320
360
400
440
480
520
560
600
305

Sample: 25%A1+75%G COMB.
Size: 31.28 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 26-Aug-86 Time: 14:06:11
File: COAL/ANTH.15 COAL .02
Operator: 1402-86-85
Plotted: 10-Sep-86 11:32:01

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		33.7	59.0	0.48	1.54
OXIDATION		152.0		0.73	2.33
COMBUSTION	428.6	470.9	530.4	27.84	89.01
ASH	Residue at 732.1 °C			3.49	11.17

Modified Sample Weight: 31.28 mg

Sample: 25%A1+75%G COMB.
Size: 31.28 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 26-Aug-86 Time: 14:06:11
File: COAL/ANTH.15 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 9:57:10

Temp [deg]	Sig-A [%]
400.0	93.993
405.2	93.217
410.1	92.417
415.0	91.541
420.1	90.515
425.1	89.438
430.2	88.131
435.1	86.898
440.1	85.062
445.1	83.118
450.0	80.848
455.1	78.217
460.0	75.120
465.1	71.316
470.1	67.178
475.1	62.707

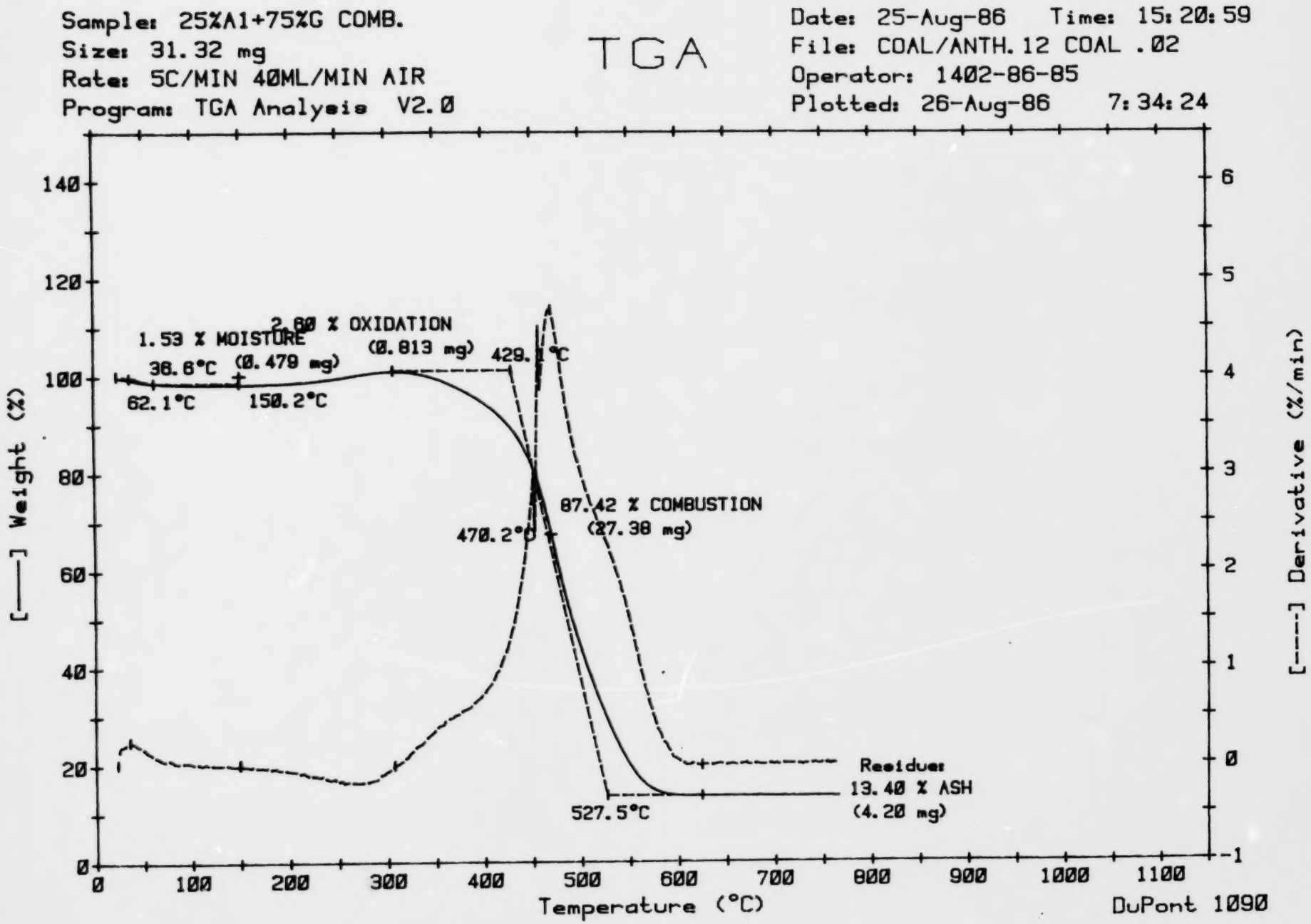
75 $\frac{5.1}{1.804} \times .12 = 460$

Temp [deg]	Sig-A [%]
480.1	58.260
485.1	54.082
490.2	50.019
495.1	46.410
500.2	43.050
505.1	39.911
510.1	36.951
515.0	34.138
520.0	31.478
525.2	28.850
530.1	26.501
535.0	24.282
540.0	22.144
545.1	20.184
550.2	18.432
555.0	16.868
560.2	15.587

50 — 410.7

25 $\frac{4.9}{2.219} \times 1.5 = \frac{3.3}{530.1}$

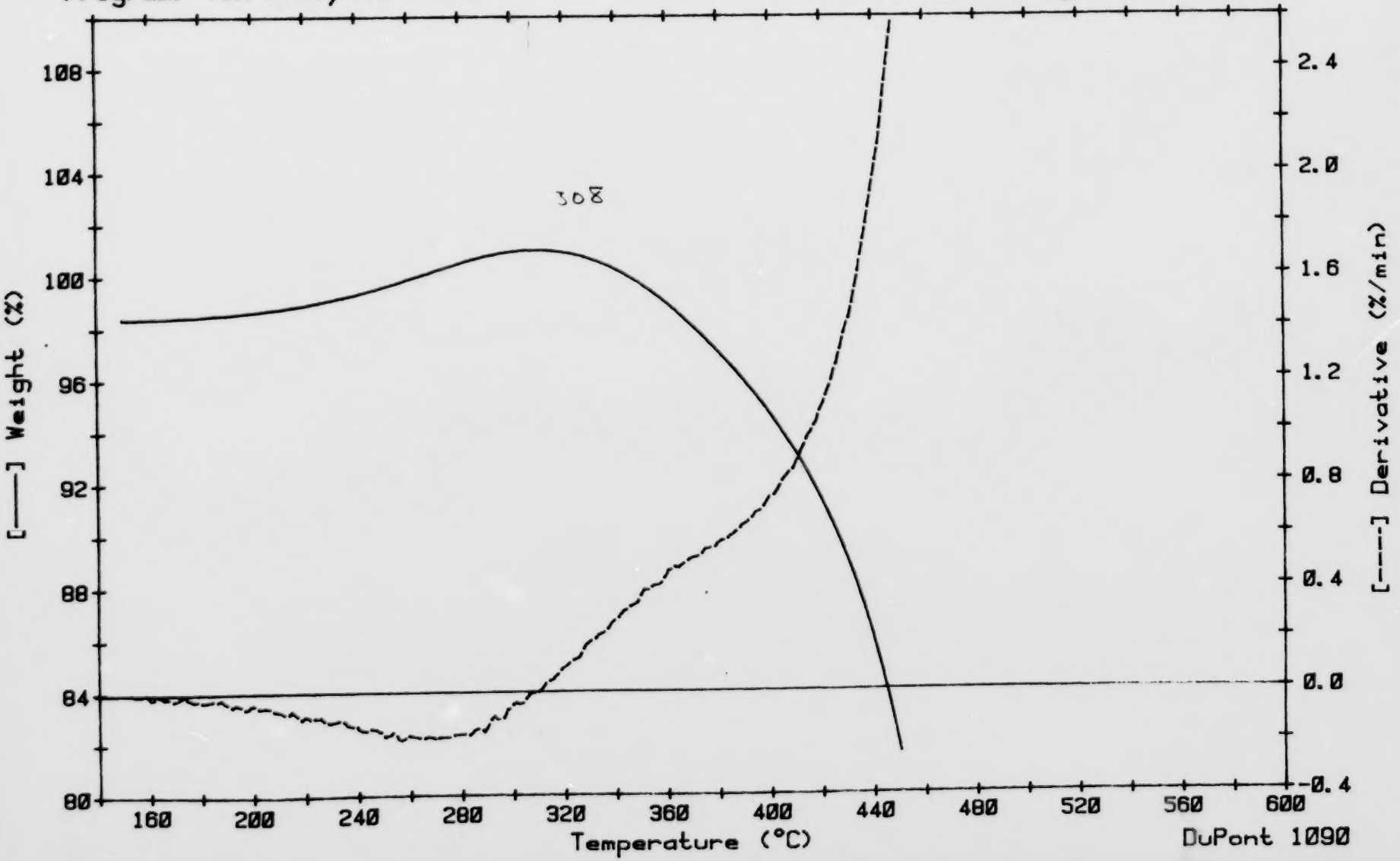
533


Sample: 25%A1+75%G COMB.
Size: 31.32 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0
TGA
Date: 25-Aug-86 Time: 15:20:59
File: COAL/ANTH.12 COAL .02
Operator: 1402-86-85
Plotted: 26-Aug-86 7:34:24
1.53 % MOISTURE
36.6°C (0.479 mg)
62.1°C
150.2°C
2.60 % OXIDATION
(0.813 mg)
429.1°C
87.42 % COMBUSTION
(27.38 mg)
470.2°C
527.5°C
Residue:
13.40 % ASH
(4.20 mg)
[——] Weight (%)
[----] Derivative (%/min)
Temperature (°C)
DuPont 1090

Sample: 25%A1+75%G COMB.
Size: 31.32 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 25-Aug-86 Time: 15:20:59
File: COAL/ANTH.12 COAL .02
Operator: 1402-86-85
Plotted: 26-Aug-86 7:53:26



Sample: 25%A1+75%G COMB.
Size: 31.32 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 25-Aug-86 Time: 15:20:59
File: COAL/ANTH.12 COAL .02
Operator: 1402-86-85
Plotted: 26-Aug-86 8:25:08

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		36.6	62.1	0.48	1.53
OXIDATION		150.2		0.81	2.60
COMBUSTION	429.1	470.2	527.5	27.38	87.42
ASH	Residue at 767.4 °C			4.20	13.40

Modified Sample Weight: 31.32 mg

Sample: 25%A1+75%G COMB.
Size: 31.32 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 25-Aug-86 Time: 15:20:59
File: COAL/ANTH.12 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 9:47:06

Temp [deg]	Sig-A [%]
400.2	94.565
405.2	93.824
410.1	93.074
415.1	92.186
420.2	91.186
425.1	90.152
430.2	88.881
435.1	87.508
440.2	85.784
445.1	83.874
450.1	81.562
455.1	79.381
460.3	75.422
465.1	71.736
470.2	67.314

75 $\frac{4.8}{3.686} \times .422 = 460.9$

Temp [deg]	Sig-A [%]
475.2	62.754
480.0	58.510
485.2	54.253
490.2	50.524
495.0	47.228
500.0	44.124
505.1	40.906
510.0	38.137
515.0	35.359
520.2	32.721
525.0	30.320
530.2	27.839
535.2	25.616
540.1	23.557
545.0	21.663
550.0	19.974

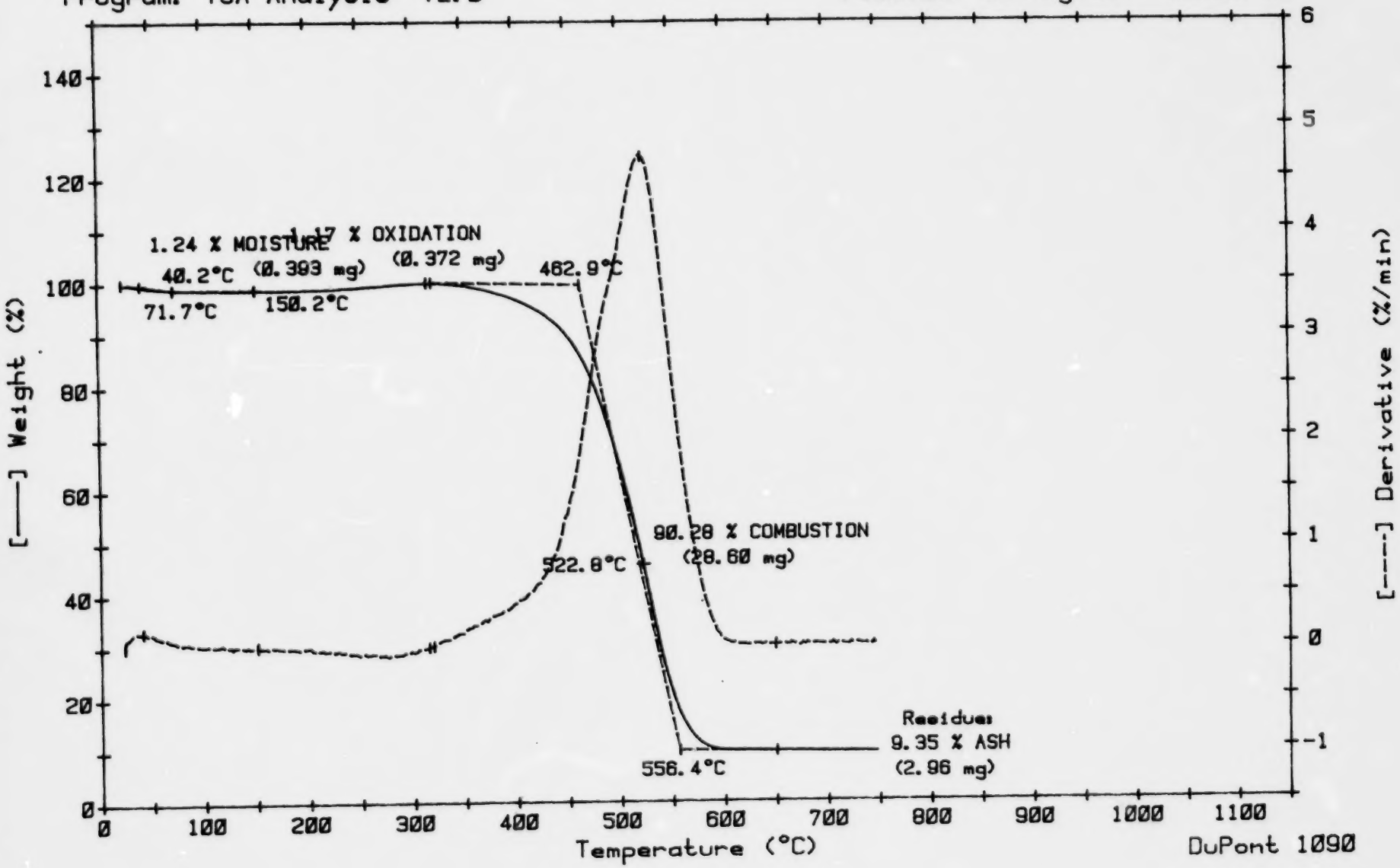
50 $\frac{4.8}{3.276} \times 0.524 = 491$

25 $\frac{4.9}{2.5?} \times .616 \quad \frac{1.5}{535.2} = 537$

Sample: 50%A1+50%G COMB.
Size: 31.68 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 25-Aug-86 Time: 12:24:56
File: COAL/ANTH.11 COAL .02
Operator: 1402-86-85
Plotted: 25-Aug-86 16:36:48



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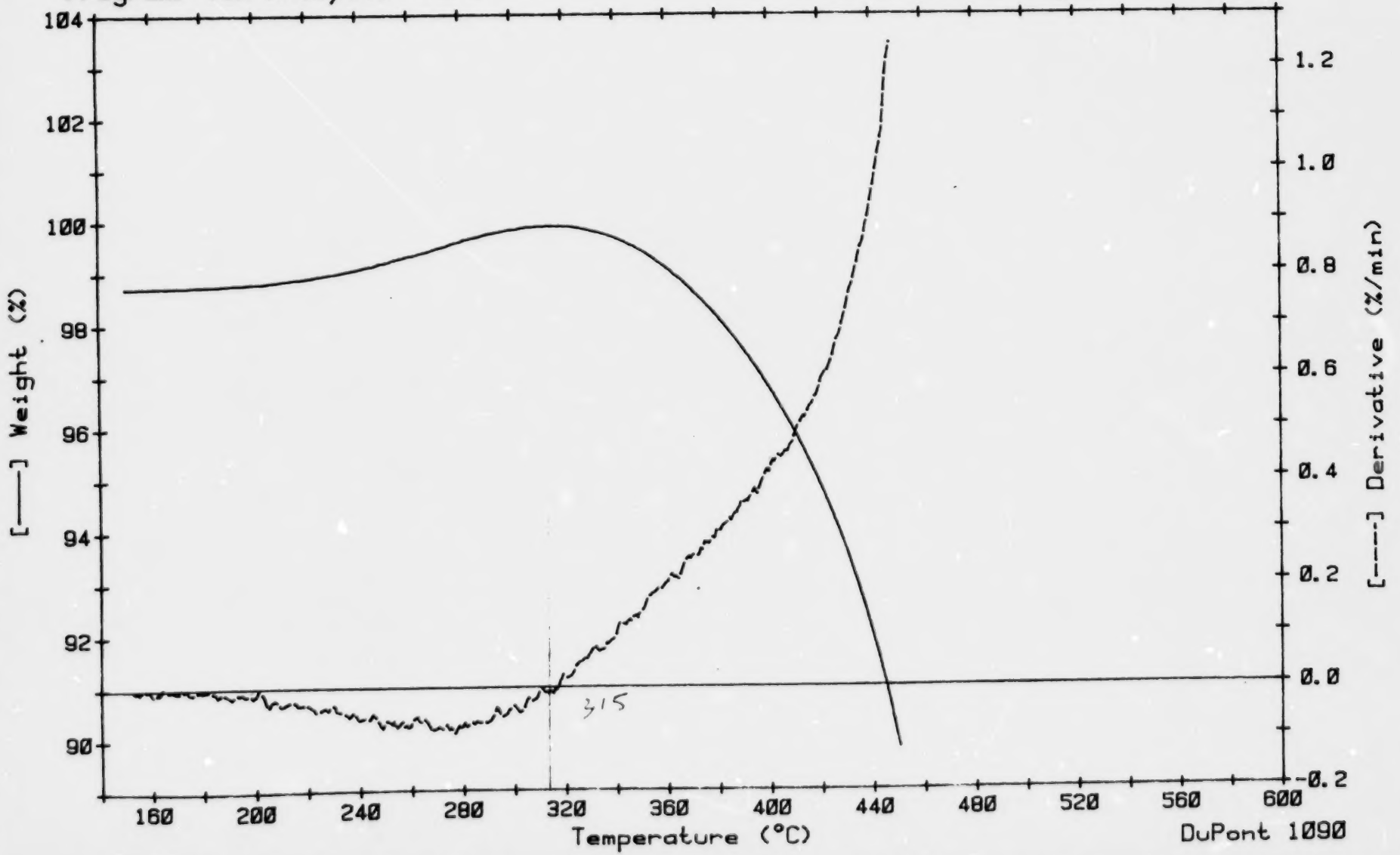
Sample: 50%A1+50%G COMB.
Size: 31.68 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 25-Aug-86 Time: 12:24:56
File: COAL/ANTH.11 COAL .02
Operator: 1402-86-85
Plotted: 25-Aug-86 16:43:07



Sample: 50%A1+50%G COMB.
Size: 31.68 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 25-Aug-86 Time: 12:24:56
File: COAL/ANTH.11 COAL .02
Operator: 1402-86-85
Plotted: 25-Aug-86 17:02:55

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		40.2	71.7	0.39	1.24
OXIDATION		150.2		0.37	1.17
COMBUSTION	462.9	522.8	556.4	28.60	90.28
ASH	Residue at 750.0 °C			2.96	9.35

Modified Sample Weight: 31.68 mg

3. cil

Sample: 50%A1+50%G COMB.
Size: 31.68 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 25-Aug-86 Time: 12:24:56
File: COAL/ANTH.11 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 8:57:30

Temp [deg]	Sig-A [%]
450.1	89.812
455.0	88.505
460.0	86.997
465.0	85.229
470.0	83.181
475.1	80.814
480.1	78.150
485.2	75.221
490.1	72.087
495.0	68.767
500.0	65.251
505.1	61.305
510.0	57.300
515.2	52.844
520.1	48.188
525.2	43.252
530.0	38.385
535.1	33.354
540.0	28.778
545.1	24.593
550.0	21.158

75 $\frac{4.9}{3.134} \times 0.221 = .34$ 485.2 486

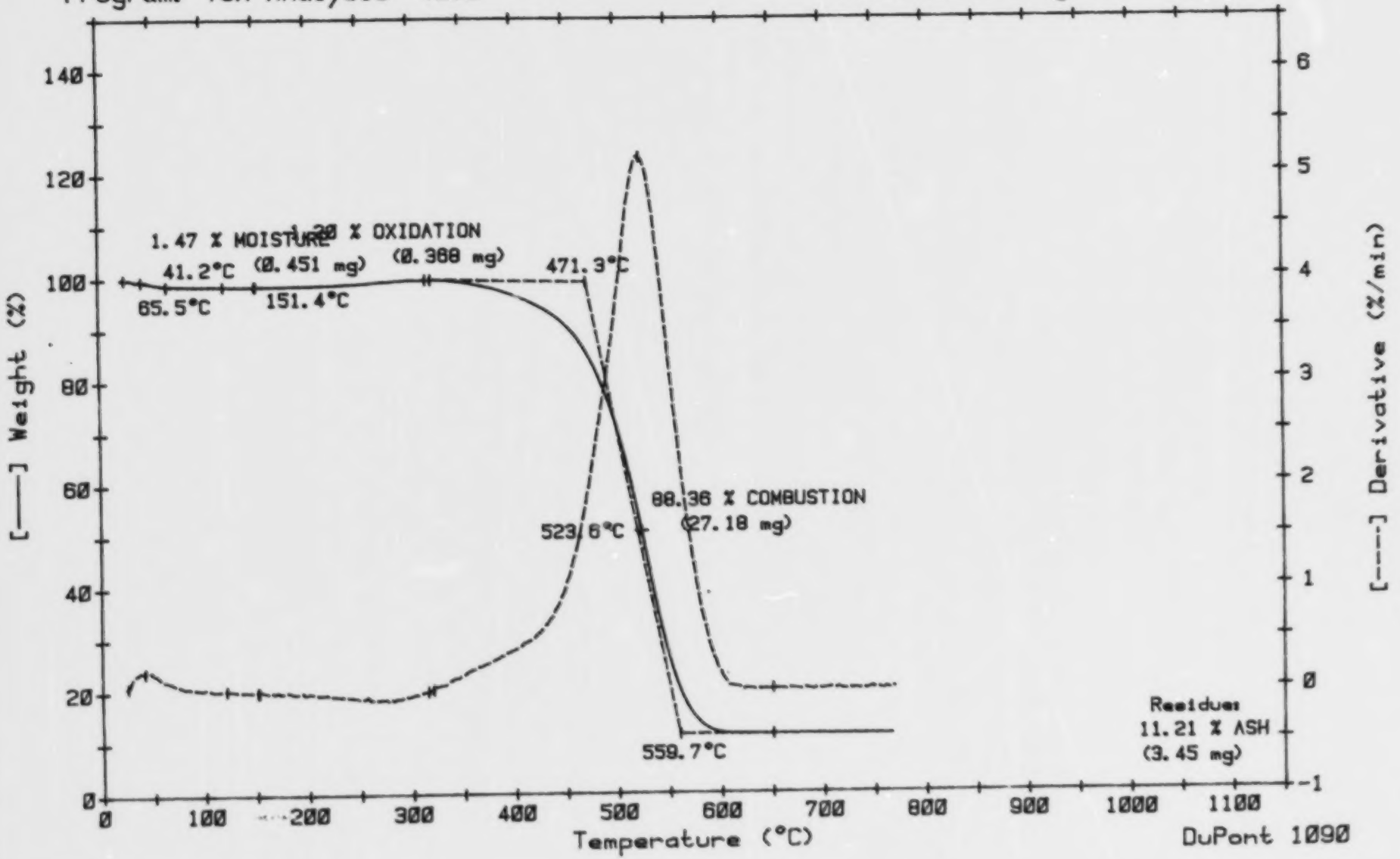
80 $\frac{4.9}{4.646} \times 2.844$ 3.0 515.2 518

25 $\frac{5.1}{4.185} \times 3.778$ 4.6 = 545

Sample: 75%A1+25%G COMB.
Size: 30.76 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 25-Aug-86 Time: 8:59:44
File: COAL/ANTH.10 COAL .02
Operator: 1402-86-85
Plotted: 25-Aug-86 15:16:11



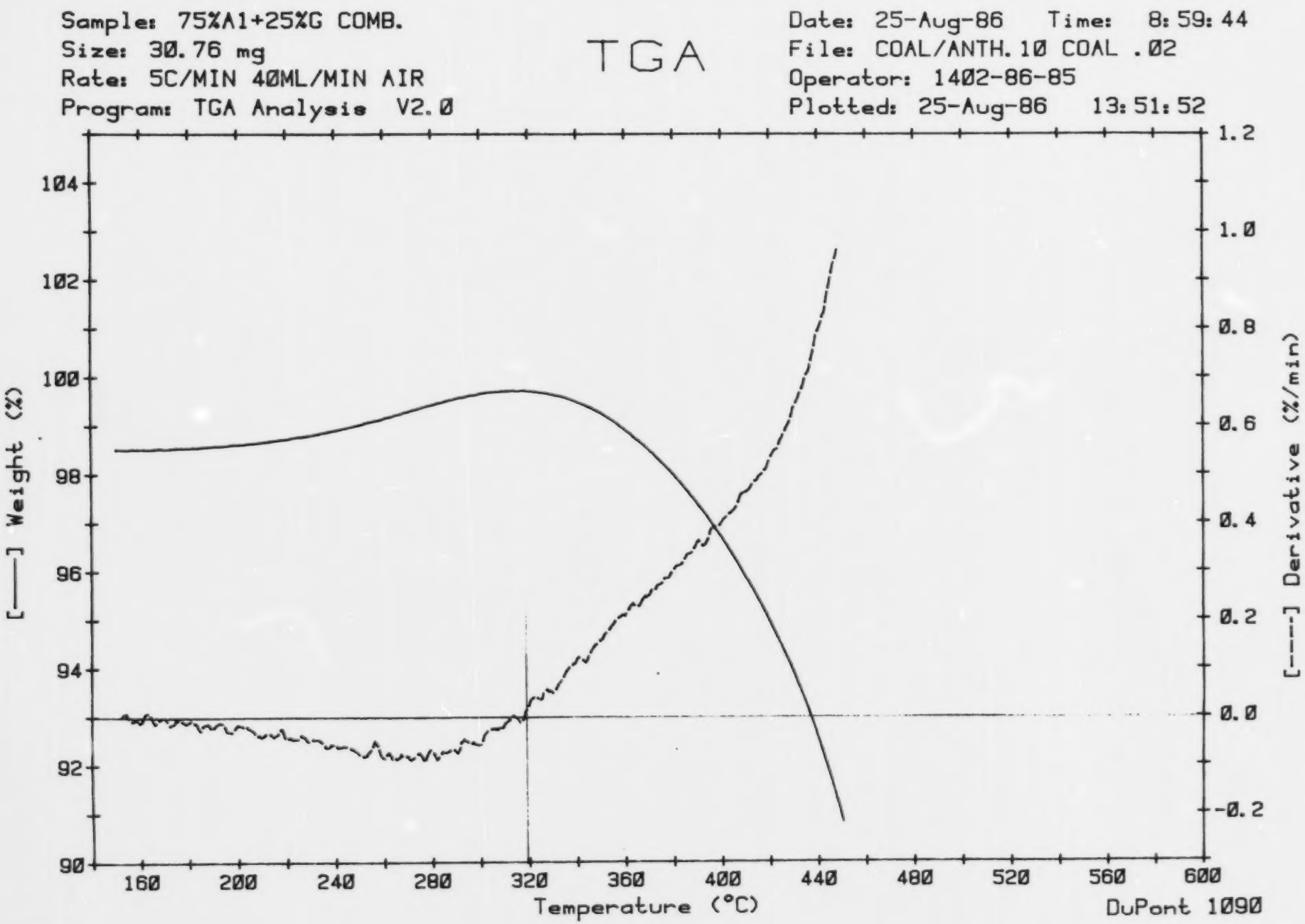
DuPont 1090

Sample: 75%A1+25%G COMB.
Size: 30.76 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 25-Aug-86 Time: 8:59:44
File: COAL/ANTH.10 COAL .02
Operator: 1402-86-85
Plotted: 25-Aug-86 16:22:49

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		41.2	67.9	0.46	1.50
OXIDATION		151.4		0.37	1.20
COMBUSTION	470.7	523.1	559.7	27.18	88.37
ASH	Residue at 771.2 °C			3.45	11.21

Modified Sample Weight: 30.76 mg


Sample: 75%A1+25%G COMB.
Size: 30.76 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0
TGA
Date: 25-Aug-86 Time: 8:59:44
File: COAL/ANTH.10 COAL .02
Operator: 1402-86-85
Plotted: 25-Aug-86 13:51:52
[——] Weight (%)
[----] Derivative (%/min)
104
102
100
98
96
94
92
90
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
160
200
240
280
320
360
400
440
480
520
560
600
Temperature (°C)
DuPont 1090

3.5c

Sample: 75%A1+25%G COMB.
Size: 30.76 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 25-Aug-86 Time: 8:59:44
File: COAL/ANTH.10 COAL .02
Operator: 1402-86-85
Plotted: 11-Sep-86 16:06:39

Temp [deg]	Sig-A [%]
480.5	81.582
485.4	79.232
490.5	76.815
495.0	74.034
500.1	70.832
505.2	67.253
510.2	63.290
515.1	58.977
520.4	53.912
525.1	48.287
530.2	44.183
535.4	38.852
540.0	34.402
545.1	29.991
550.1	26.128
555.0	22.820
560.0	20.037
565.0	17.749
570.1	15.918
575.2	14.485
580.4	13.418

75 $\frac{4.5}{2.581} \times 1.615 = \frac{2.8}{490.5}$ — 113

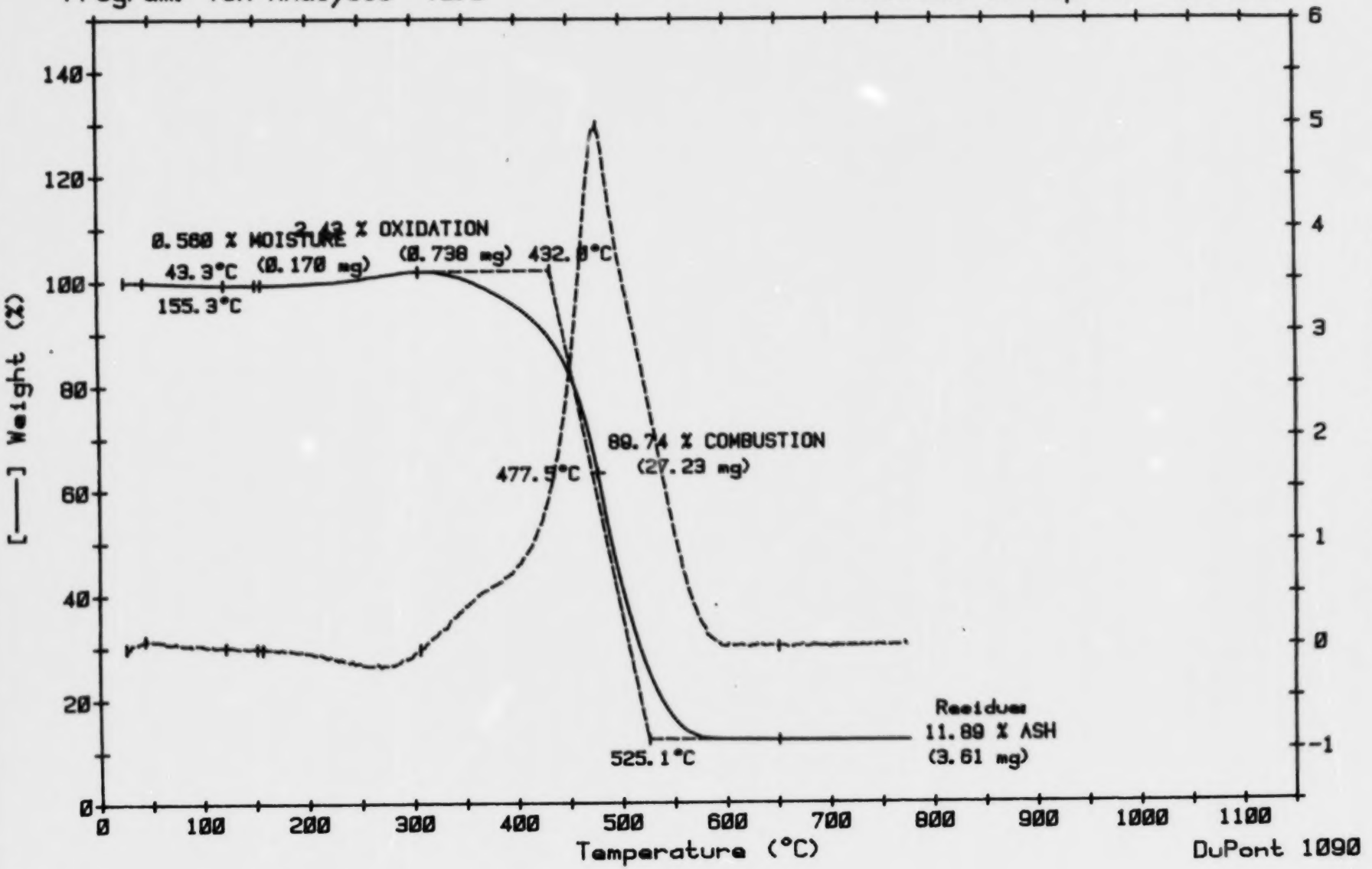
50 $\frac{4.7}{4.645} \times 3912 = \frac{3.9}{520.4}$ — 524

25 $\frac{4.9}{3.306} \times 1.126$ $\frac{1.7}{550.1}$ 552

Sample: 25%A2+75%G COMB.
Size: 30.34 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 4-Sep-86 Time: 13:57:04
File: COAL/ANTH.18 COAL .02
Operator: 1402-86-85
Plotted: 11-Sep-86 14:16:59



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Sample: 25%A2+75%G COMB.
Size: 30.34 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 4-Sep-86 Time: 13:57:04
File: COAL/ANTH.18 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 11:09:28

Temp [deg]	Sig-A [%]
450.2	82.358
455.0	78.966
460.3	76.970
465.1	73.839
470.0	70.062
475.2	65.419
480.0	60.479
485.1	55.070
490.2	50.107
495.1	45.714
500.1	41.654
505.0	37.857
510.0	34.311
515.1	30.884
520.1	27.665
525.1	25.241
530.0	22.892
535.0	20.798
540.1	18.897
545.2	17.206
550.1	15.987

> 75 $\frac{4.8}{3.131} \times 1.97 = 3.0$ 460.7

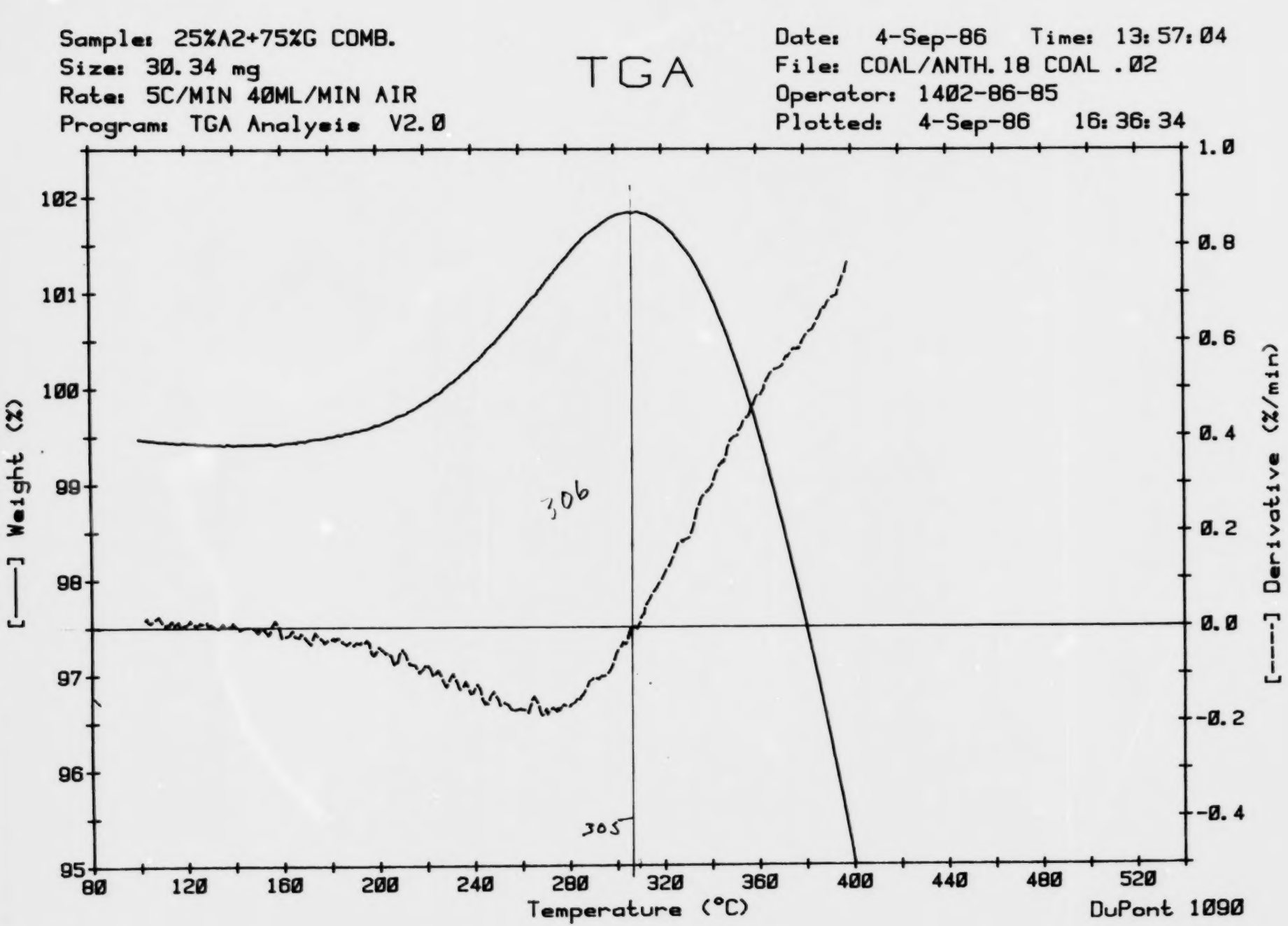
163

> 50 $\frac{4.9}{9.393} \times .1 =$

490

> 25 $\frac{4.9}{2.347} \times .24 =$

526


Sample: 25%A2+75%G COMB.
Size: 30.34 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0
TGA
Date: 4-Sep-86 Time: 13:57:04
File: COAL/ANTH.18 COAL .02
Operator: 1402-86-85
Plotted: 4-Sep-86 16:36:34
[——] Weight (%)
[----] Derivative (%/min)
Temperature (°C)
DuPont 1090
306
305

Sample: 25%A2+75%G COMB.
Size: 30.34 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 4-Sep-86 Time: 13:57:04
File: COAL/ANTH.18 COAL .02
Operator: 1402-86-85
Plotted: 11-Sep-86 14:32:48

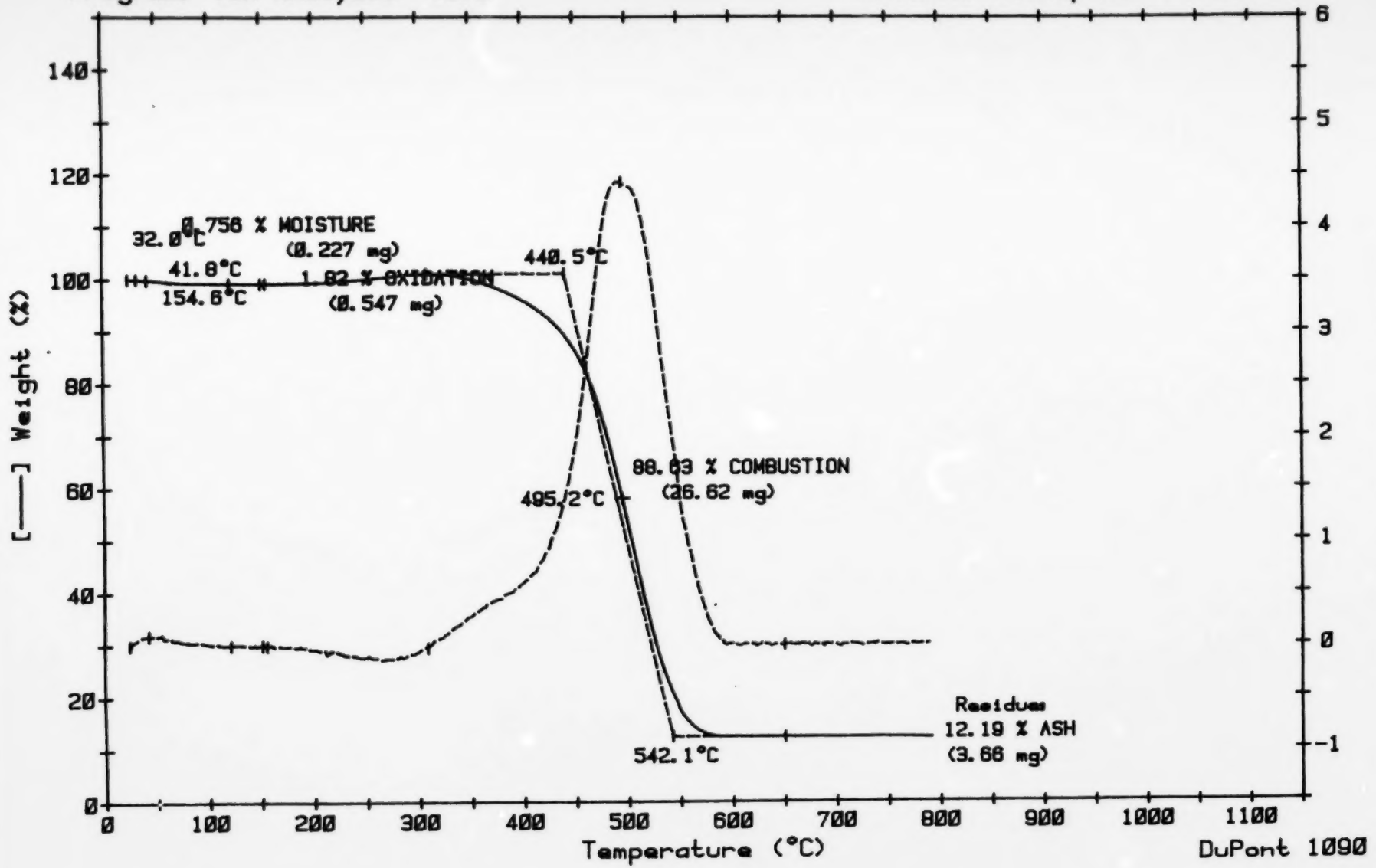
Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		43.3		0.17	0.56
OXIDATION		155.3		0.74	2.43
COMBUSTION	432.0	477.5	525.1	27.23	89.74
ASH	Residue at 779.0 °C			3.61	11.89

Modified Sample Weight: 30.34 mg

Sample: 50%A2+50%G COMB.
Size: 30.04 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 4-Sep-86 Time: 8:52:59
File: COAL/ANTH.17 COAL .02
Operator: 1402-86-85
Plotted: 11-Sep-86 13:57:21

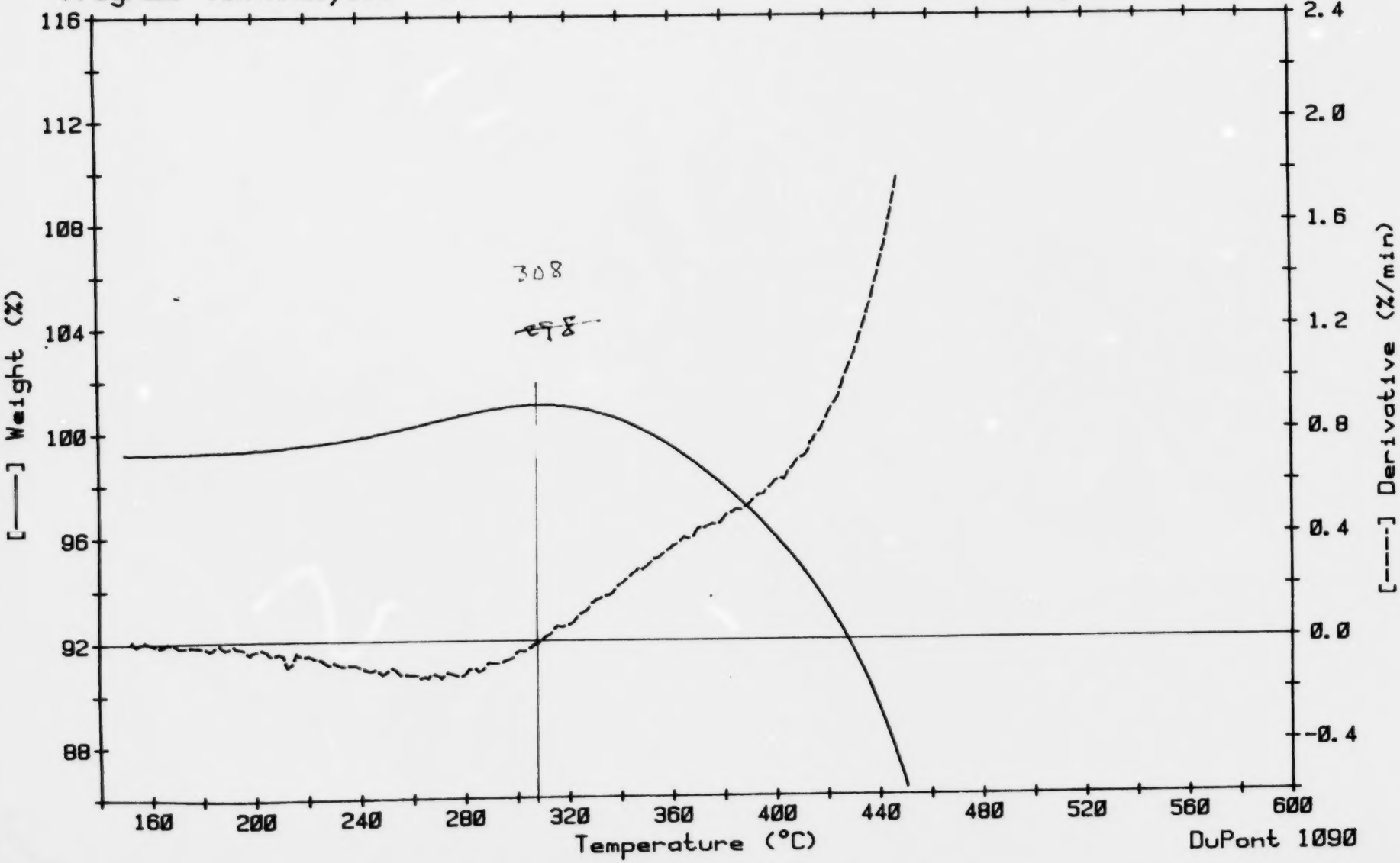


DuPont 1090

Sample: 50%A2+50%G COMB.
Size: 30.04 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 4-Sep-86 Time: 8:52:59
File: COAL/ANTH.17 COAL .02
Operator: 1402-86-85
Plotted: 4-Sep-86 15:51:55



Sample: 50%A2+50%G COMB.
Size: 30.04 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 4-Sep-86 Time: 8:52:59
File: COAL/ANTH.17 COAL .02
Operator: 1402-86-85
Plotted: 11-Sep-86 14:04:25

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE	32.0	41.8		0.23	0.76
OXIDATION		154.6		0.55	1.82
COMBUSTION	440.5	495.2	542.1	26.62	88.63
ASH	Residue at 792.3 °C			3.66	12.19

Modified Sample Weight: 30.04 mg

Sample: 50%A2+50%G COMB.
Size: 30.04 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 4-Sep-86 Time: 8:52:59
File: COAL/ANTH.17 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 10:37:17

Temp [deg]	Sig-A [%]
450.1	86.370
455.2	84.508
460.1	82.452
465.2	80.061
470.2	77.288
475.1	74.159
480.2	70.526
485.2	66.668
490.2	62.493
495.2	58.065
500.1	53.657
505.2	49.040
510.0	44.512
515.1	39.937
520.1	35.639
525.0	31.684
530.1	27.836
535.2	24.643
540.1	22.013
545.2	19.696
550.1	17.362

> 75 $\frac{4.9}{3.139} \times 2288 \times \frac{3.6}{470.2} = 174$

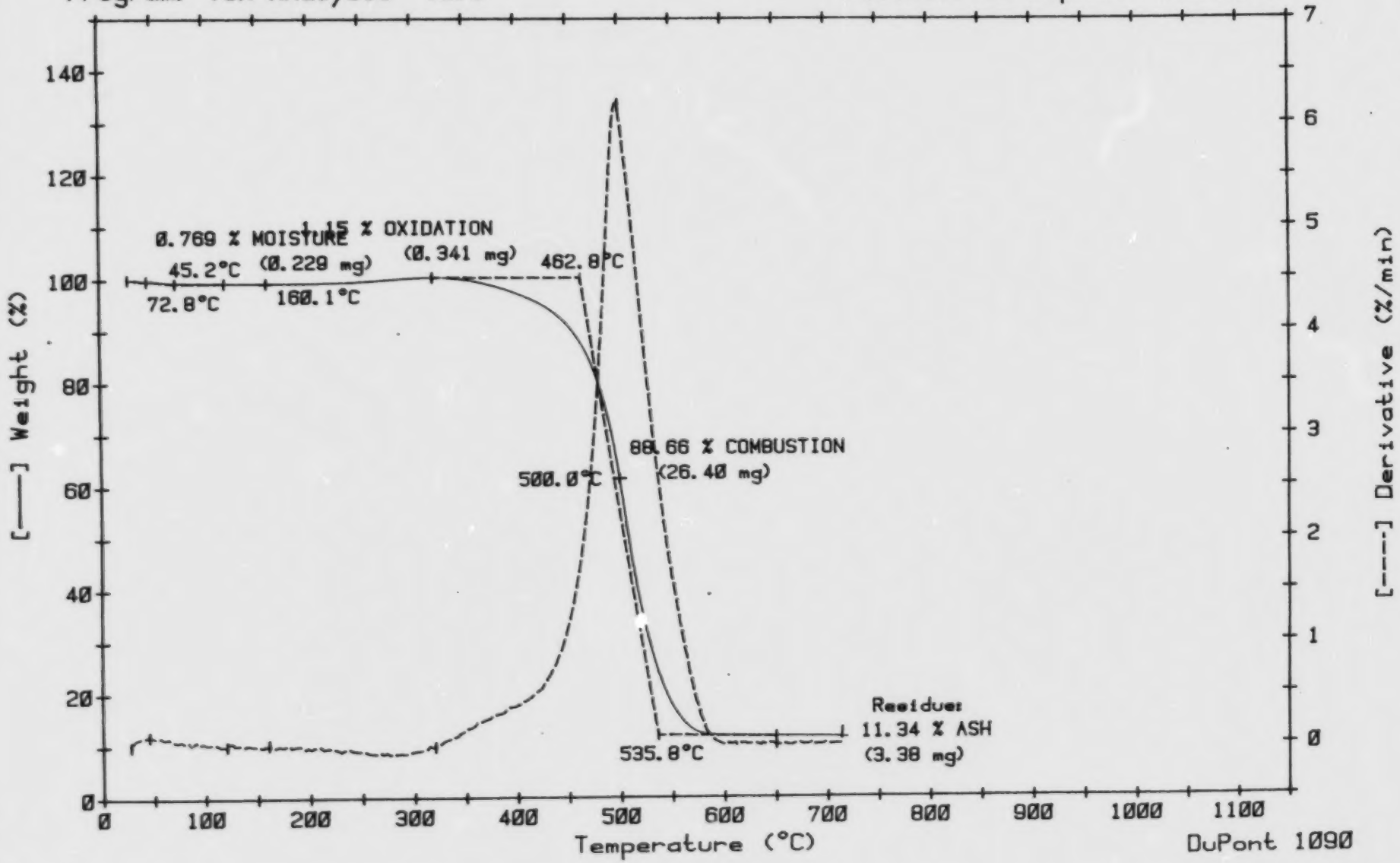
> 50 $\frac{5.1}{4.617} \times 3.657 = \frac{4.0}{500.1} = 104$

> 25 $\frac{5.1}{3.193} \times 2.836 \times \frac{4.5}{[illegible]} = 535$

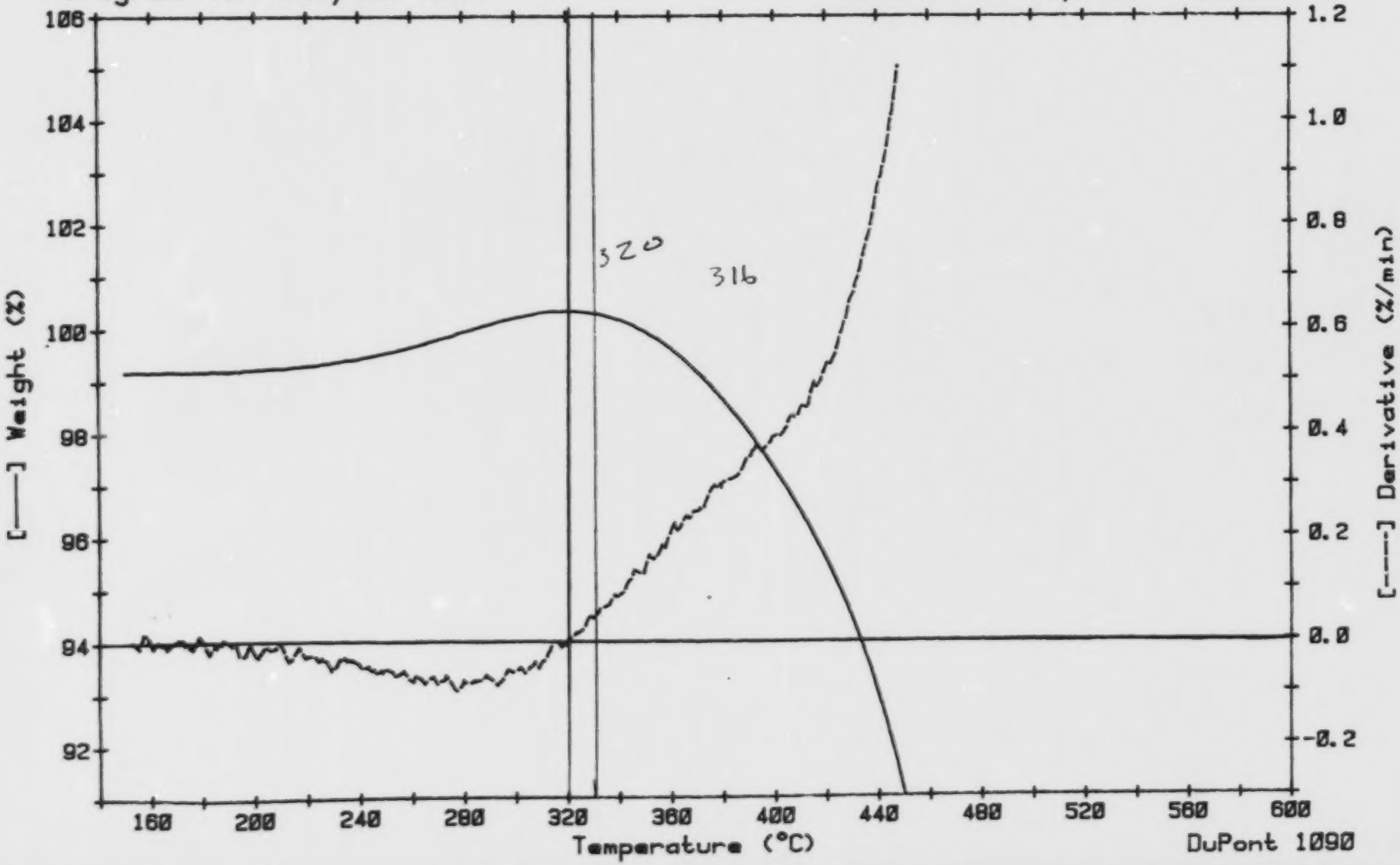
Sample: 75%A2+25%G COMB.
Size: 29.78 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

TGA

Date: 12-Sep-86 Time: 12:20:02
File: COAL/ANTH.23 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 15:58:02



DuPont 1090


Sample: 75%A2+25%G COMB.
Size: 29.78 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0
TGA
Date: 12-Sep-86 Time: 12:20:02
File: COAL/ANTH.23 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 15:20:36
320
316
[——] Weight (%)
[----] Derivative (%/min)
Temperature (°C)
DuPont 1090

Sample: 75%A2+25%G COMB.
Size: 29.78 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: TGA Analysis V2.0

Date: 12-Sep-86 Time: 12:20:02
File: COAL/ANTH.23 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 16:04:32

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		45.2	72.8	0.23	0.77
OXIDATION		160.1		0.34	1.15
COMBUSTION	462.8	500.0	535.8	26.40	88.66
ASH	Residue at 721.6 °C			3.38	11.34

Modified Sample Weight: 29.78 mg

Sample: 75%A2+25%G COMB.
Size: 29.78 mg
Rate: 5C/MIN 40ML/MIN AIR
Program: General Analysis V1.0

Date: 12-Sep-86 Time: 12:20:02
File: COAL/ANTH.23 COAL .02
Operator: 1402-86-85
Plotted: 12-Sep-86 16:12:43

Temp [deg]	Sig-A [%]
450.2	90.890
455.1	89.770
460.2	88.331
465.0	86.892
470.0	84.711
475.1	82.303
480.1	79.519
485.2	76.111
490.1	72.285
495.1	67.302
500.0	61.439
505.1	54.602
510.1	48.014
515.0	42.261
520.1	36.870

Temp [deg]	Sig-A [%]
525.0	32.328
530.0	28.359
535.2	24.706
540.0	22.002
545.1	19.531
550.0	17.576
555.1	15.941
560.2	14.584
565.2	13.593
570.1	12.868
575.1	12.385
580.2	12.089
585.0	11.938
590.2	11.861
595.1	11.824
600.2	11.810

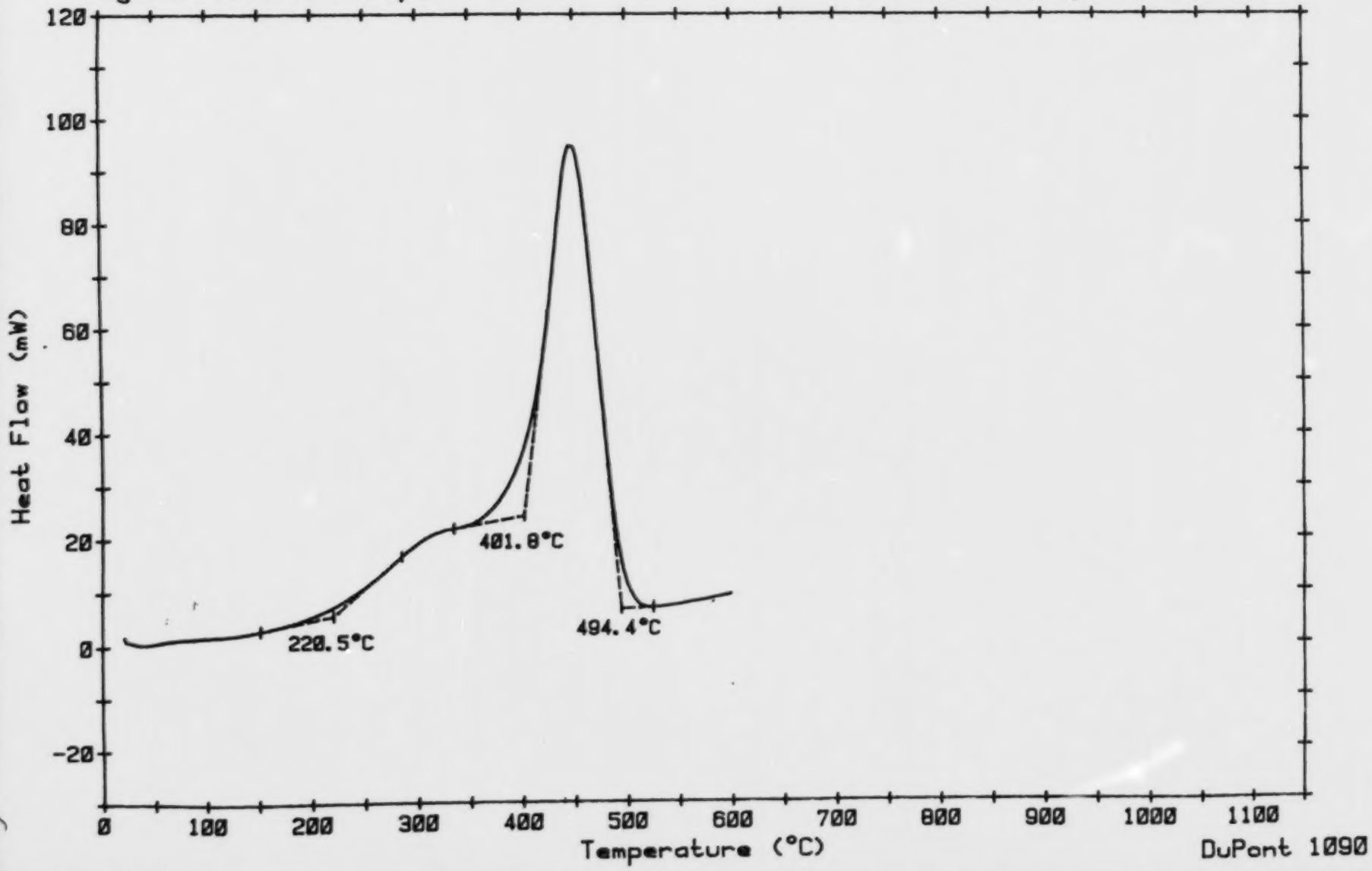
APPENDIX 4

DSC Profiles

Sample: COAL C
Size: 6.75MG
Rate: 5C/MIN AIR
Program: General Analysis V1.0

DSC

Date: 19-Sep-86 Time: 9:00:49
File: COAL/ANTH.32 COALDSC.02
Operator: 1402-86-85
Plotted: 19-Sep-86 11:01:05

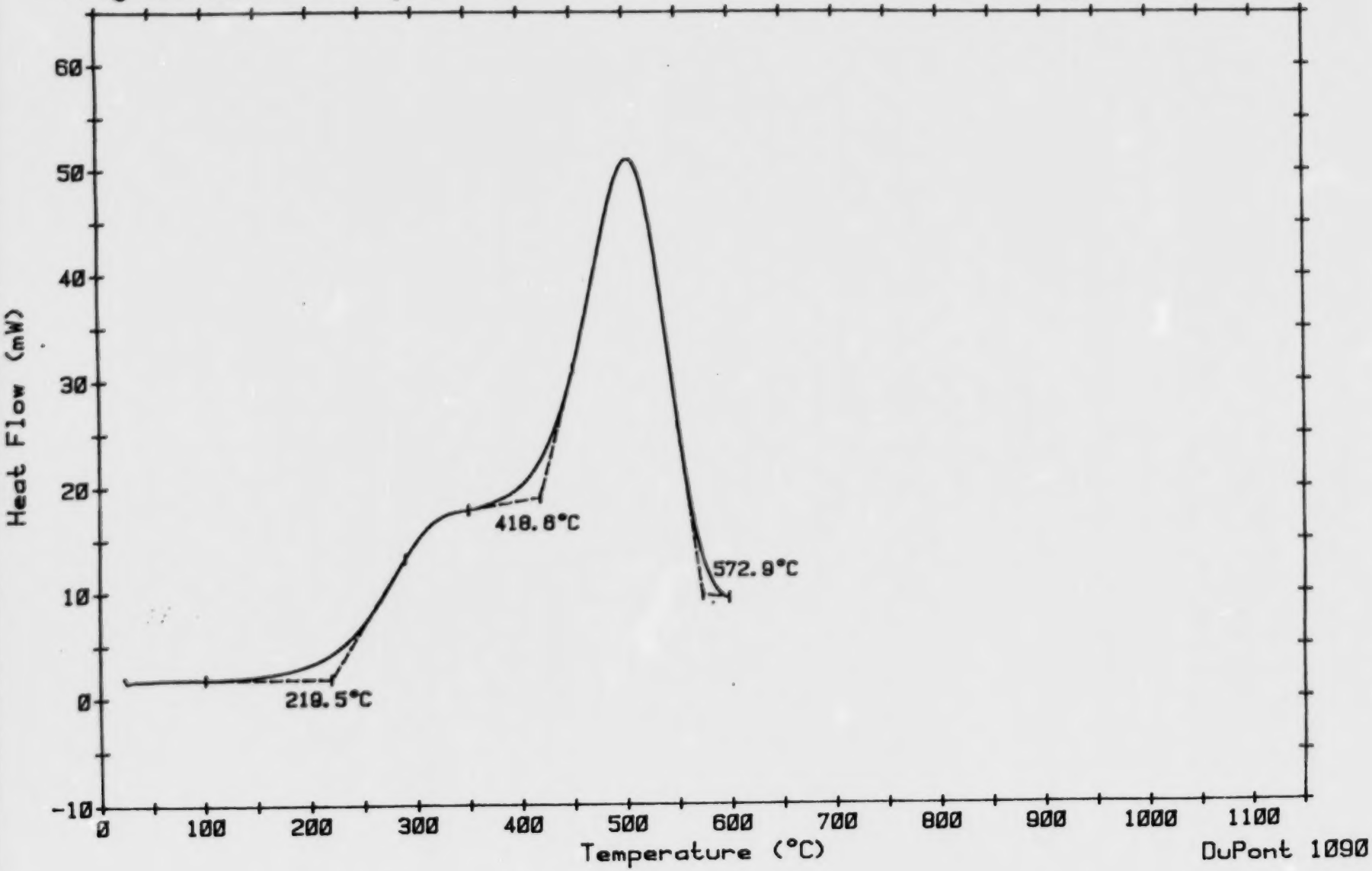


DuPont 1090

Sample: COAL G
Size: 5.70
Rate: 5C/MIN AIR
Program: General Analysis V1.0

DSC

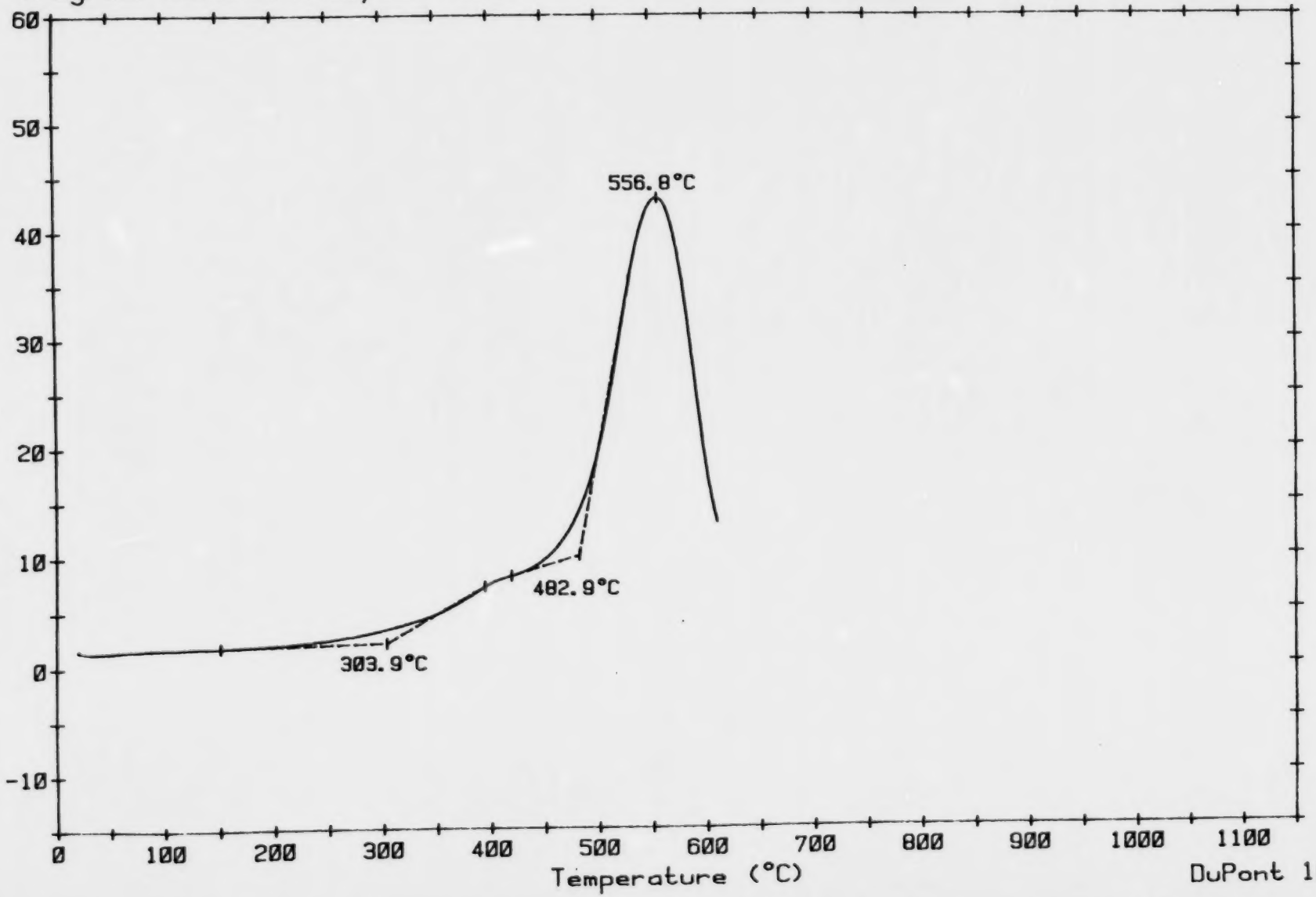
Date: 17-Sep-86 Time: 13:50:56
File: COAL/ANTH.30 COALDSC.02
Operator: 1402-86-85
Plotted: 17-Sep-86 15:50:31



Sample: ANTHRCITE A1
Size: 3.04
Rate: 5C/MIN AIR
Program: General Analysis V1.0

DSC

Date: 7-Oct-86 Time: 11:19:16
File: COAL/ANTH.36 COALDSC.02
Operator: 1402-86-85
Plotted: 7-Oct-86 13:48:01

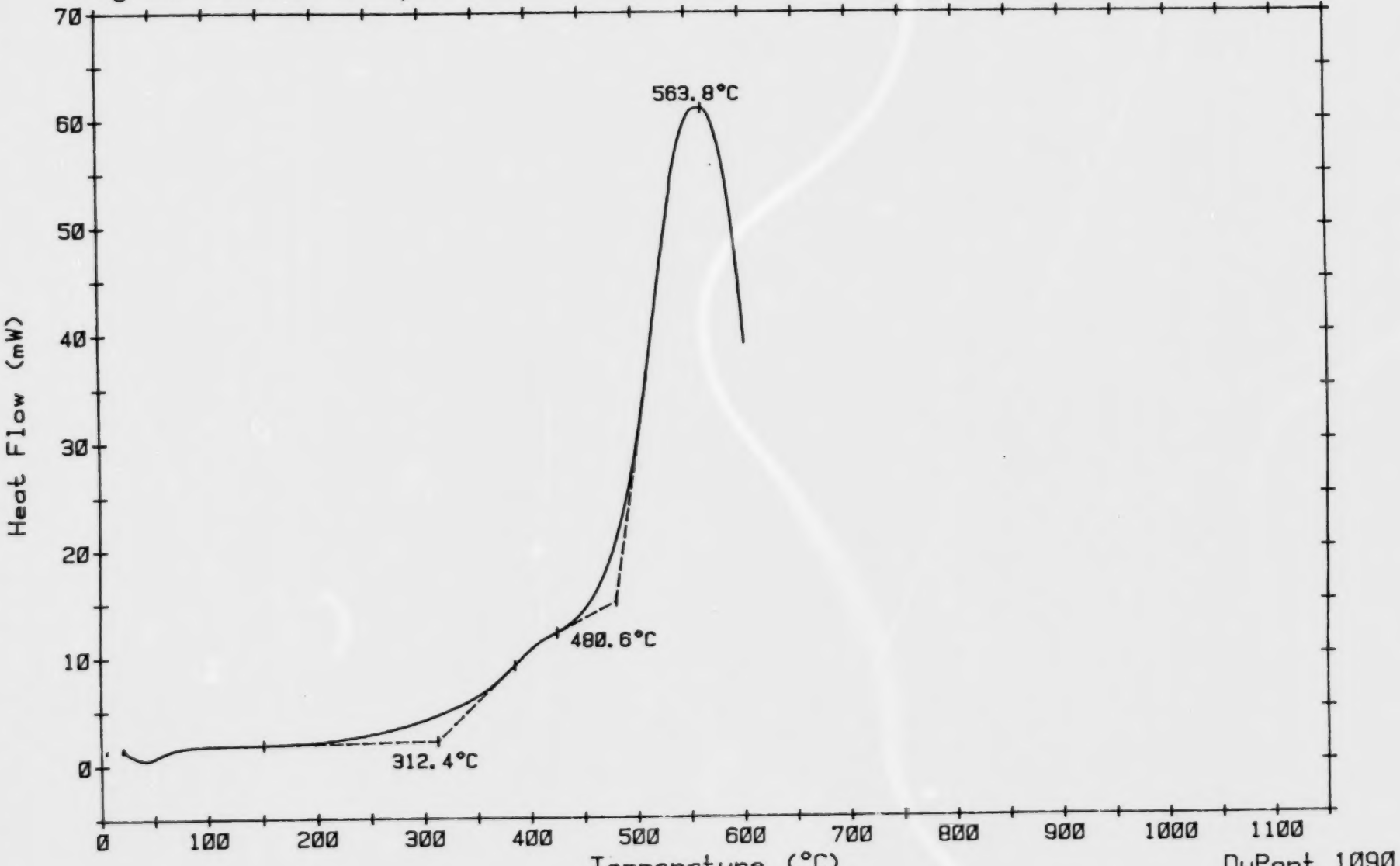


DuPont 1090

Sample: ANTHRACITE A1
Size: 5.85MG
Rate: 5C/MIN AIR
Program: General Analysis V1.0

DSC

Date: 1-Oct-86 Time: 14:18:19
File: COAL/ANTH.33 COALDSC.02
Operator: 1402-86-85
Plotted: 1-Oct-86 16:20:00

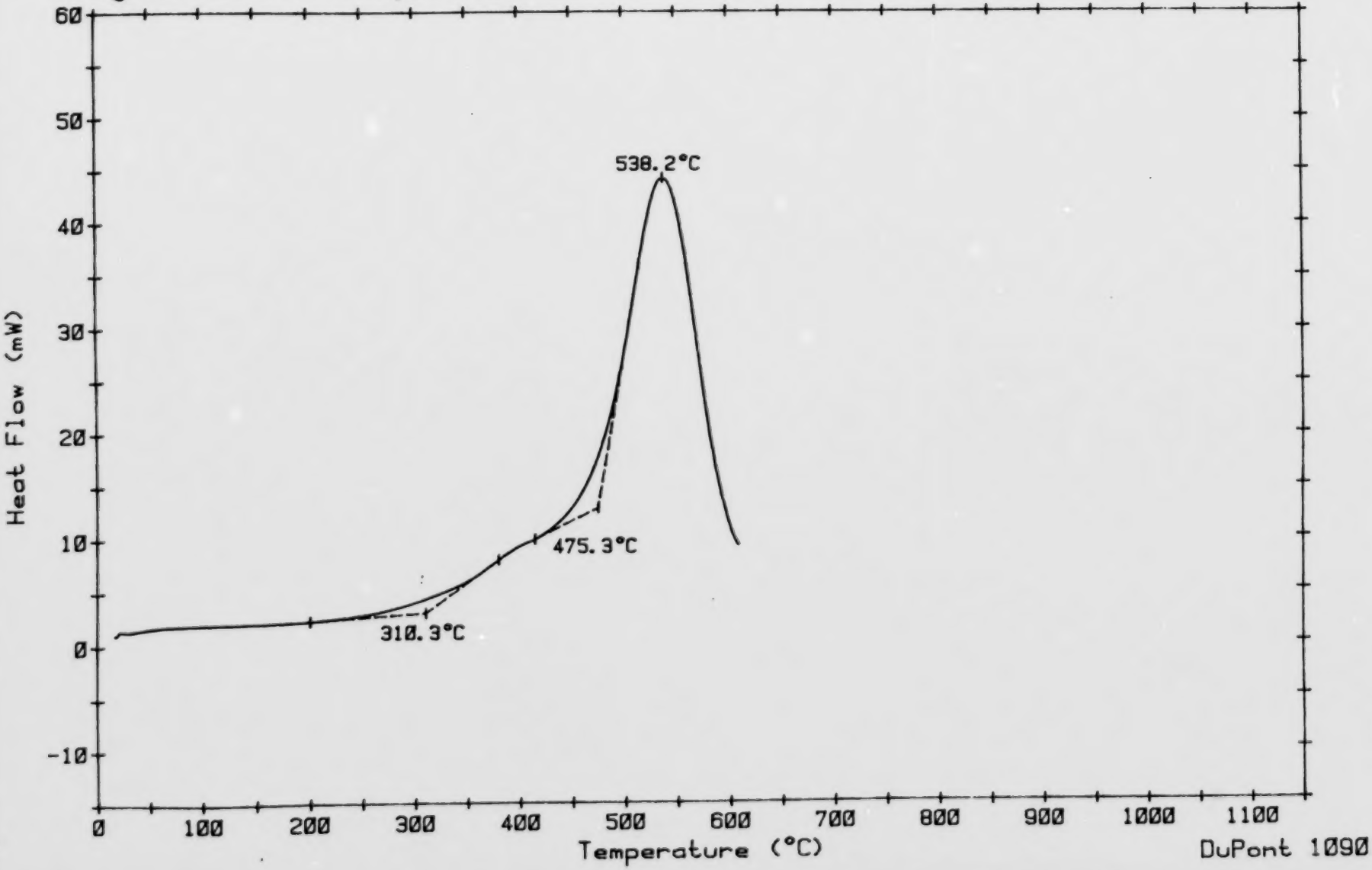


DuPont 1090

Sample: ANTHRCITE A2
Size: 3.48MG
Rate: 5C/MIN AIR
Program: General Analysis V1.0

DSC

Date: 7-Oct-86 Time: 14:19:45
File: COAL/ANTH.37 COALDSC.02
Operator: 1402-86-85
Plotted: 9-Oct-86 9:40:24

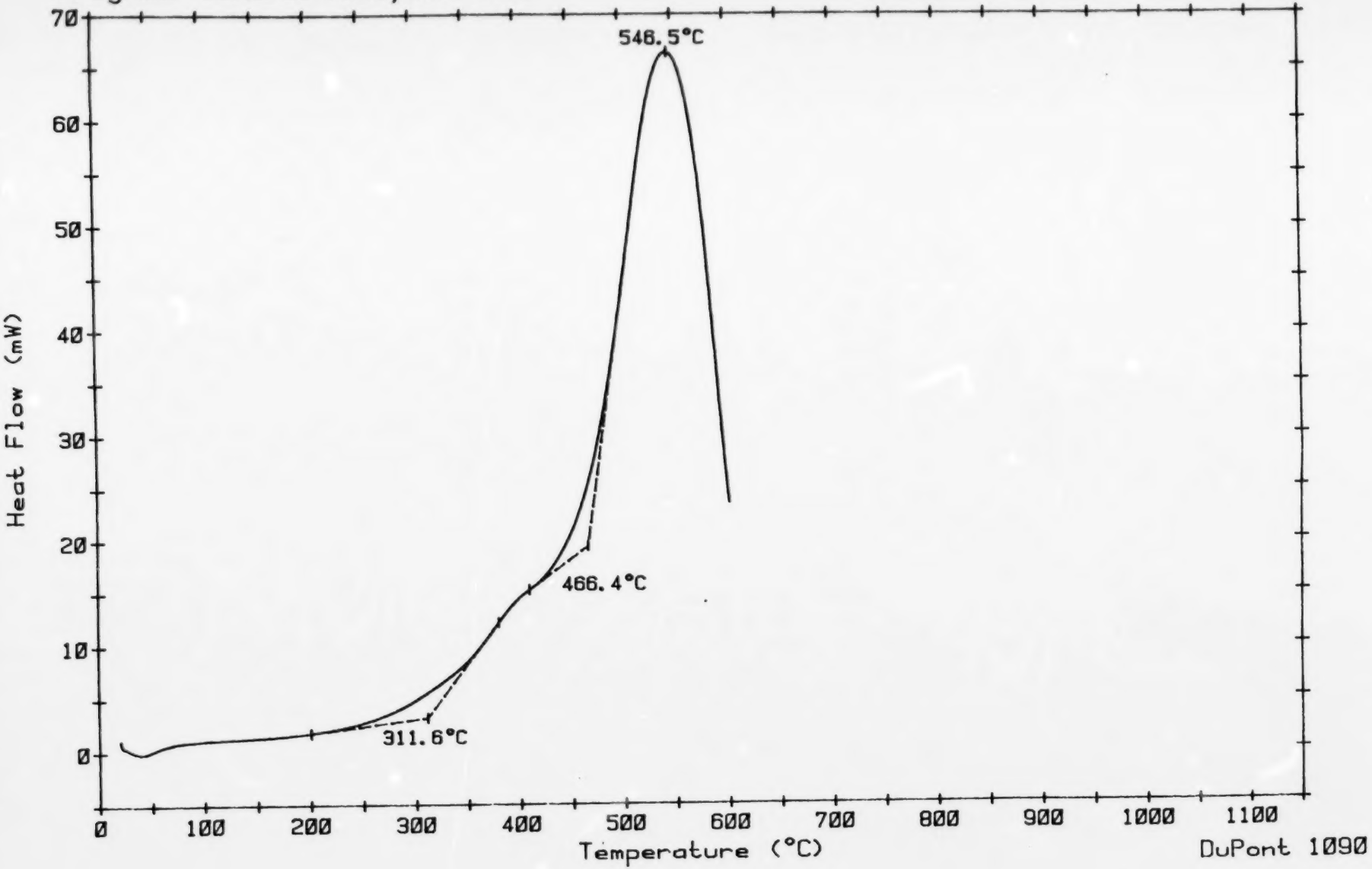


DuPont 1090

Sample: ANTHRACITE A2
Size: 7.01MG
Rate: 5C/MIN AIR
Program: General Analysis V1.0

DSC

Date: 2-Oct-86 Time: 7:23:29
File: COAL/ANTH.34 COALDSC.02
Operator: 1402-86-85
Plotted: 2-Oct-86 9:42:30



DuPont 1090

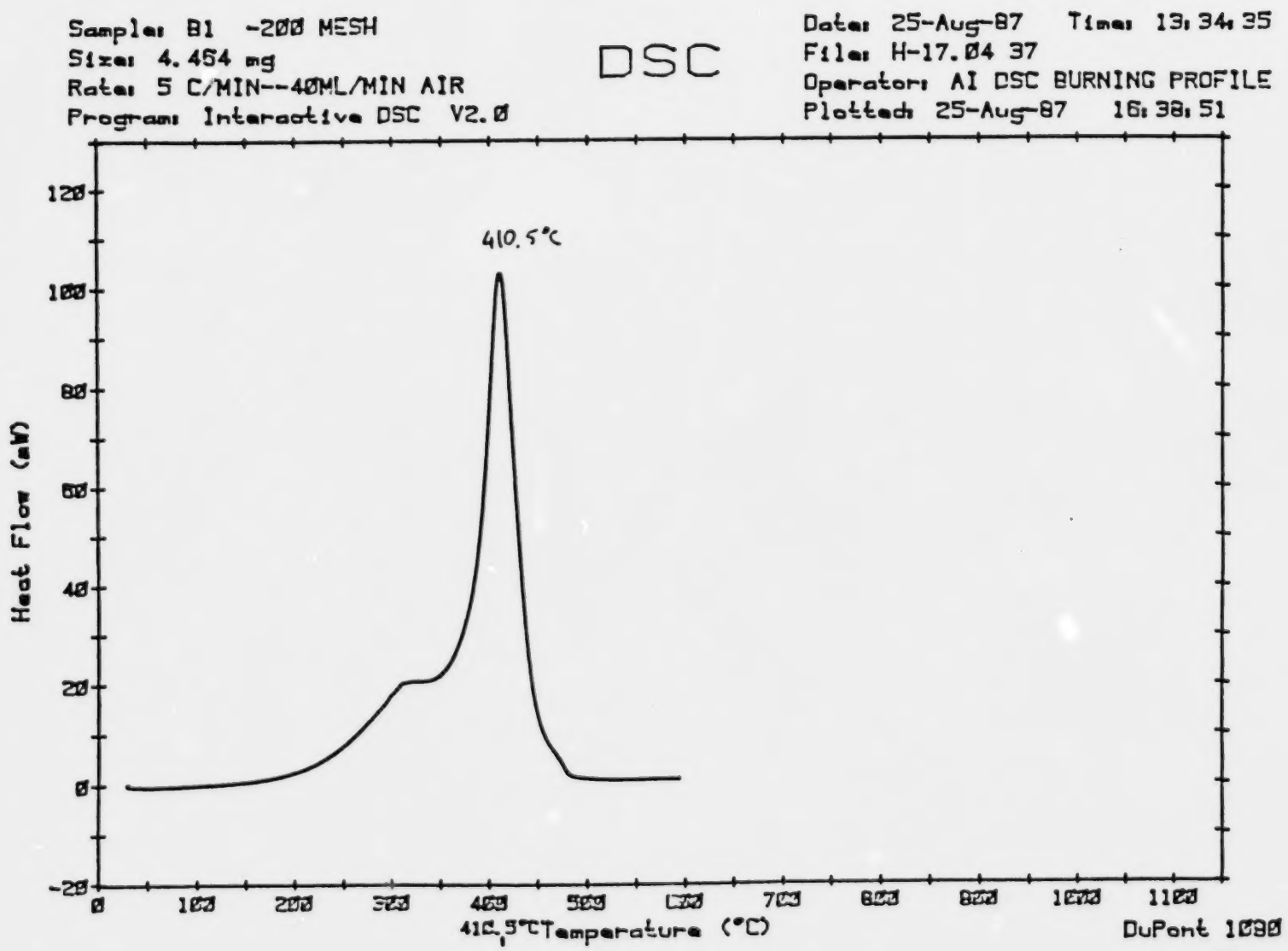


Figure 3.18 DSC Profile for Sample B1

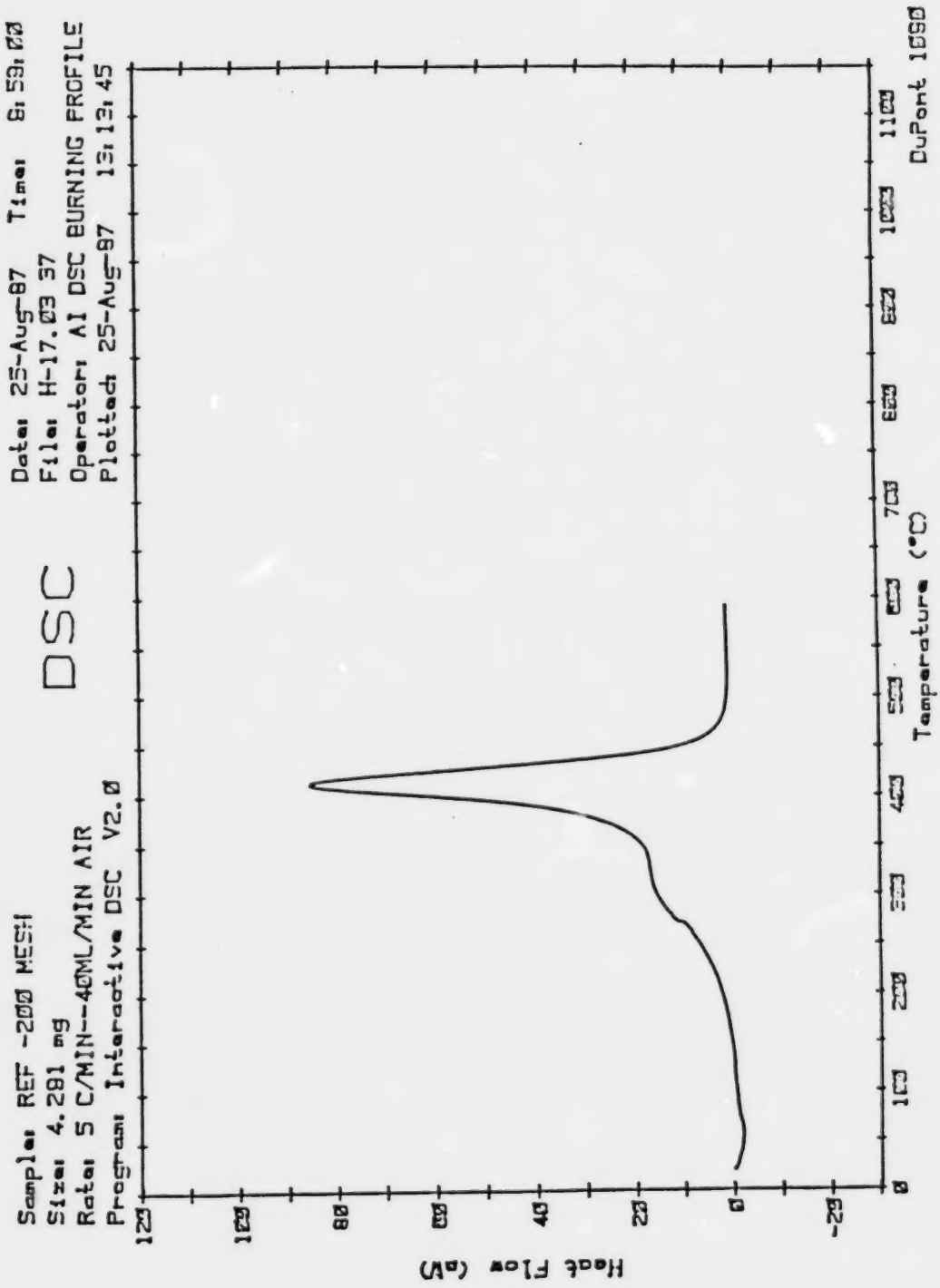


Figure 3.12 DSC Profile for Sample 0

APPENDIX 5

ARC Sub-Contractor Report

Evaluation of the Combustibility of Anthracite/Thermal Coal Mixtures

by

A.K. Chambers and D.E. Ungarian

Submitted on behalf of the
Alberta Research Council
Coal Research Department to
Gulf Canada Corporation

Final Report for Work Performed
Under Contract # PS 8694 - DSS # 23440-6-9058
September 1987

Date Submitted: September 1987

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Energy Resources Division
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P.O. Bag #1310
Devon, Alberta, Canada T0C 1E0

Telephone: (403) 987-8118

ABSTRACT

The combustibility of anthracite/thermal coal blends, micronized anthracite/thermal coal blends and a beneficiated coal was measured using a flammability index test and an entrained flow combustion test. With the beneficiated sample and its parent coal a thermogravimetric pyrolysis and combustion profile and a differential scanning calorimeter profile were also determined.

Results indicate that the combustion reactivity decreased with increasing coal rank. Blending anthracite of conventional grind with thermal coal appeared to give a lower carbon burnout than anticipated in the shorter residence times studied on the entrained flow combustor. In the flammability index test, blending resulted in flammability index temperatures lower than expected. Micronizing dramatically improved both the flammability and the rate of burnout of the anthracite. In contrast to the anthracite/thermal coal blends, the micronized anthracite/thermal coal blends combusted on the EFC at rates predicted by simple additivity of the combustion rates of the separate coals. The beneficiated product tested had essentially the same combustion properties as the original coal.

The experimental results and conclusions from these results given in this report were obtained using small scale combustion tests. Combustion tests at this scale are not totally representative of conditions which occur in a pulverized coal flame. Experiments at a larger scale would be required to confirm the conclusions about flammability and carbon burnout reached in this study and to examine other combustion properties, such as flame stability and ash fouling and slagging properties.

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1. INTRODUCTION

Anthracite is a high heating value fuel which suffers from a low combustion reactivity relative to coal in pulverized coal combustion systems. The low combustion reactivity is caused by both a low volatile matter content, resulting in poor ignition properties and a low char reactivity, resulting in poor carbon burnout of the char remaining after devolatilization.

The effect of reducing particle size on the combustion properties of anthracite was studied by Beer (1969). Both the ignition and burnout characteristics were improved by reducing the particle size from 20% less than 76 μm to 100% less than 76 μm. Reduction of particle size to sizes significantly below that of typical pulverized coal (70% less than 74 μm) is termed 'micronizing'. Other studies of combustion properties of micronized bituminous coals confirm the trend of improved combustion properties with reduction in particle size (Briceland et al., 1983).

Blending of anthracite with a thermal coal of higher combustion reactivity could possibly give a product of higher heating value with adequate combustion characteristics. Combustion experiments performed by Lee (1983) using blends of low and high reactivity bituminous coals indicated an enhanced burnout of the lower reactivity coal due to the presence of the high reactivity coal. This observation may or may not apply for mixtures of anthracite and bituminous coal.

Several techniques for increasing the calorific value of coal (for example by removing moisture or ash) are available for the production of a 'beneficiated' coal. However, to produce a saleable product these treatments should improve or at least maintain the combustion properties of the original coal. The impact of a treatment process on combustion properties can be assessed experimentally.

This report describes the results of ignition and carbon burnout tests using laboratory scale experiments. The relative ignition temperatures and carbon burnout rates of anthracite, micronized anthracite, mixtures of anthracite and thermal coals and a beneficiated product made from a thermal coal

were compared using a laboratory-scale entrained flow combustor. The slow heating rate pyrolysis and combustion properties of the beneficiated coal were also studied using a thermogravimetric analyser and a differential scanning calorimeter. Conclusions are given on the effects on the combustion properties of micronizing, blending and beneficiation on the samples studied. Recommendations for further experimental studies are made.

This work was performed under sub-contract to Gulf Canada Corp. under their Contract DSS # 23440-6-9058 with Department of Supplies and Services, Canada.

2. METHODOLOGY

2.1 Sample Preparation

Six samples were supplied by Gulf Canada Corporation for combustion tests. These samples were prepared from Mount Klappan anthracite, and coal from Coal Valley, Goodrich and Obed Mountain mines. In addition, samples of micronized anthracite and a beneficiated Obed Mountain coal were also supplied. All samples were labelled and are listed in Table 2.1. Further discussion of the samples in this report will refer to these labels.

A -200 mesh sample was used in all the combustion tests. Table 2.2 gives the proportion of sample passing through a 200 mesh screen as received from Gulf Canada Corporation. The +200 mesh fraction of sample A1 was repulverized to obtain at least 70% of sample -200 mesh. Samples O and B1 as received were not pulverized and were thus air dried, pulverized by hand, and stored in sealed containers. To ensure proper identification of samples, proximate and ultimate analysis of samples of the -200 mesh fraction were done.

Particle size measurements of the -200 mesh fraction were made for all samples using a CiLAS Laser Granulometer, Model 715, to determine average particle sizes and the size distribution.

2.2 TGA and DSC Tests

Thermogravimetric pyrolysis and combustion tests were performed on samples O and B1 using a Dupont Instruments Corp., Model 951 thermogravimetric analyzer (TGA) shown in Figure 2.1, and associated Model 1090 microprocessor. The techniques used were as requested by Gulf Canada Corporation. The pyrolysis test consisted of heating an approximate 30 mg sample of pulverized coal at a rate of 5°C/min in a flow of 40 ml/min of nitrogen to a maximum temperature of 950°C. The combustion test consisted of heating an approximate 30 mg pulverized sample also at 5°C/min in a flow of 40 ml/min of air. For both tests, the weight of sample and temperature of furnace was recorded at two second intervals during the run.

Differential scanning calorimetry experiments were performed on Samples O and B1 using a Model 910 Differential Scanning Calorimeter (DSC). The method used consisted of heating an approximate 7 mg pulverized sample at 5°C/min in air up to a maximum temperature of 600°C. In this equipment, the heat flow from the sample due to the combustion was monitored during the run. Sample size was adjusted to keep the maximum heat flow within the measuring range of the equipment.

2.3 Entrained Flow Combustion Tests

Entrained flow combustion tests were performed using the Alberta Research Council entrained flow combustor (EFC) which is shown schematically in Figure 2.2. Development of the equipment and technique used in these experiments is described in detail by Knill (1987). The purpose of the EFC tests was to measure the burnout rate of the feed material in a particle-gas suspension at carefully controlled conditions of reactor temperature, residence time and oxygen concentration. The stoichiometric air ratio was kept above five to ensure an approximate constant gas temperature and composition during the combustion to allow direct comparison of burnout between samples and also to prevent excessive heat buildup due to temperature limitation of the equipment to less than 1100°C.

The EFC consisted of a syringe type coal feeder, an isothermal reactor, water-cooled injector and collector, and an unburnt solids collection system. The coal feeder is shown in Figure 2.3. The sample was loaded into the syringe and installed onto the motorized syringe feeder. A primary gas stream flowed through the feeder to carry sample to the reactor as the syringe pushed the sample out. A vibrator connected to the feeder helped to ensure even flow of the sample. Sample was fed to the reactor at a controlled rate of 0.04 ± 0.01 g/min in the primary air stream at a flowrate of 0.5 l/min. Sufficient sample, depending on estimated extent of burnout, was fed to result in enough approximately 5-10 mg of residue for ash determination using the TGA. Details of the design of the reactor and water-cooled injector and collector are shown in Figure 2.4. The particles entered the reactor through a water-cooled injector and mixed with 4.0 l/min of secondary air preheated to reactor temperature. The reactor temperature was controlled from a three zone furnace

around the reactor tube and was measured using suction pyrometers installed in the reactor. The particles ignited and burned for a fixed length of time, which was controlled by the distance between the injector and collector. Combustion was terminated by quenching the particles and gas in the water-cooled collector probe.

The reacted particles were retained in a Balston Filter attached to the end of the collector. The ash content of the residue, ash_{res}, and the coal, ash_{coal}, were determined by proximate analysis of the coal and of the residue collected in the filter using a TGA technique. The fraction of burnout was then calculated according to the expression:

$$W_{daf} = \frac{1 - ash_{coal}/ash_{res}}{1 - ash_{coal}}$$

where W_{daf} was the fractional burnout of organic matter in the char on a dry basis.

Caution must be used when calculating overall conversion using the ash balance technique. An assumption of the technique is that the ash is inert and remains solid, with all the ash in the coal appearing in the unburnt residue. At the relatively low temperatures of the tests reported here (less than 1100°C) this assumption is valid (Pace, 1982). However, an additional problem of decreasing accuracy of the calculation occurs for dry ash free (daf) conversion of less than 30%. This is illustrated in Figure 2.5, which shows the percent error in calculation of conversion for an error in determination of ash content of the residue of $\pm$2% of the ash. Assuming this accuracy of ash determination, for conversions less than 30% daf the error in conversion determination rapidly increases over 10%. Thus for conversions less than 30% daf, the repeatability of this combustion test would be poor unless ash can be determined very accurately. The estimate of $\pm$2% in determination of ash content accounts for both errors in ash determination and experimental errors in collection, sampling and handling of the unburnt residue.

2.4 Flammability Index

Flammability index tests were conducted using the EFC shown schematically in Figure 2.6 as set up to perform the test. The equipment consists of a syringe type feeder, an isothermal reactor, a reaction gas supply system and a means of detecting a flame. The EFC unit was described in detail in Section 2.3.

The flammability test was based on a technique developed by Nsakala et al (1985). An approximate 0.003 g of -200 mesh sample was injected from the feeder through the water cooled injector in a primary stream of oxygen at a flowrate of 0.2 l/min. The particles mixed rapidly with a secondary flow of oxygen of 0.35 l/min which had been preheated to the reactor temperature. The reactor temperature was controlled from a three zone furnace around the reactor tube and was measured using suction pyrometers installed in the reactor. The reactor temperature was raised in 25°C increments until ignition of the sample was observed. Ignition was characterized by a bright flash or 'explosion' in the reactor tube, as observed in a mirror at the bottom of the reactor tube. The reactor temperature was then lowered in 5°C intervals until ignition was no longer observed. The temperature of ignition thus determined was the flammability index of the sample.

3. RESULTS AND DISCUSSION

3.1 Sample Preparation and Analysis

The ultimate and proximate analyses of the anthracites, coals and beneficiated samples are shown in Table 3.1. As expected, the volatile matter content of the anthracite samples was much lower than the other samples. Ash content was similar for the anthracite samples and Samples G and C. The micronized anthracite (A2) had slightly less ash and slightly more volatile matter than the original anthracite. The different ash content may be a result of selectivity during preparation of the micronized sample while the higher volatile matter in addition be due to the smaller micronized particles liberating more volatile matter during the proximate analysis. The similar hydrogen and oxygen content of Sample A1 and A2 implies that they should have the same volatile matter content.

The beneficiation process applied to Sample O to obtain B1 has altered the coal analysis. The beneficiated product has a much lower moisture content (1.5% vs 11.2%), a lower hydrogen and oxygen content, a higher sulfur content and 3.5% daf less volatile matter. These changes would be consistent with a heat treatment process during beneficiation.

The mass median particle sizes for the -200 mesh fractions used in the combustion experiments are given in Table 3.2. Figures 3.1 to 3.6 show the weight percent distribution vs. particle size of the -200 mesh fractions. The micronized anthracite had a mean particle size less than half that of the pulverized anthracite. This is also illustrated by comparing Figure 3.1 and 3.2. The amount of sample with particles larger than 50 μm was negligible in Sample A2 while more than 30% of Sample A1 was particles larger than 50 μm. For Samples A1, G, C, O and B1 the mass median particle size and the particle size distribution was very similar. Therefore, other than Sample A2, the combustion test results should have been unaffected by particle size variations between samples.

Mixtures of Samples A1 and A2 with Samples G and C were prepared from the -200 mesh fractions to study the effect of blending on combustibility.

Table 3.3 summarizes the mixtures prepared and the labelling of these samples. Samples were prepared by weighing the portion of each followed by careful mixing prior to withdrawing a sample for the experiment.

3.2 TGA and DSC Tests of Samples 0 and B1

TGA and DSC tests were performed on Samples 0 and B1 using the procedures described in Section 2.2. The TGA experiments measured the weight loss profiles during pyrolysis and combustion at the slow heating rates typical of thermogravimetric experiments (5°C/min). The DSC experiments measured the heat produced from a combusting sample at low temperatures (<500°C). The results of these measurements are given in Figures 3.7 to 3.18.

From comparing Figures 3.7 and 3.13, the only difference in the TGA pyrolysis profile of Sample 0 and B1 was in the moisture content of the samples, with the parent coal having a higher moisture content than the beneficiated coal. This was confirmed by the proximate analysis given in Table 3.1. The temperature of onset of devolatilization, the inflection temperature and the content of volatile matter and residue were very similar for the two samples (see also figure 3.8 and 3.14).

The TGA combustion profile is given in Figure 3.9 to 3.11 for Sample 0 and Figure 3.15 to 3.17 for Sample B1. Again the moisture content of the Sample B1 is lower than Sample 0. Comparing Figures 3.10 and 3.16 the temperature of onset of oxidation of the beneficiated sample was about 33°C higher than the parent coal. However the onset, inflection and completion temperatures of the combustion phase of the TGA profile were very similar for the two samples, with temperature differences less than 8°C. Thus the TGA burnout profile for the beneficiated and original coal were very similar.

The DSC profile for the two samples is given in Figure 3.12 and 3.18. Although there was some difference in the heat release profile at the lower temperatures (around 300°C), the temperature of maximum heat release was the same, at about 410°C.

The above measurements of pyrolysis and combustion at low heating rates and temperatures on the TGA and DSC indicated that the beneficiation process had little or no effect on these combustion properties of the Obed Mountain coal.

3.3 Entrained Flow Combustion Tests

The -200 mesh fraction of all samples and mixtures were combusted at various reactor residence times at reactor temperatures of 1100°C. The equipment and experimental technique used are described in Section 2.3. EFC tests were carried out in air (21% O_2) for all samples and for some samples in 5% oxygen atmosphere. The results of all EFC tests are given in Table 3.4 and selected results are illustrated in Figures 3.19 to 3.23. The residence times given in Table 3.5 and the figures are estimated values of the particle residence time determined from a numerical model of the gas and particle flow in the reactor. As discussed in Section 2.3, these combustion tests were performed in an atmosphere of about 500% excess air so that all samples would be subjected to about the same gas temperature and oxygen concentration throughout the reactor. In all cases, sample burnout refers to burnout of the organic matter on a dry, ash-free basis.

Figure 3.19 shows the relative sample burnout of the pulverized anthracite and coal samples in both the 5% and 21% oxygen atmosphere. The samples in order of increasing burnout rate were: A1<G<C<O. This ranking corresponds to decreasing combustion reactivity with increasing coal rank. No measurable weight loss was found with Sample A1 in 5% oxygen. The anthracite weight loss even in air was only equal to the volatile matter of the feed. This would imply that at these temperatures in air the anthracite has not ignited. This is supported by the flammability index test (discussed in Section 3.4) where also the anthracite did not ignite. Both Sample C and O were very reactive with greater than 90% burnout achieved in less than 0.2 s residence time in air. Sample G was intermediate in reactivity between Sample A1 and Sample C, with a maximum burnout of 58% after 0.3 s residence time in air.

3.3.1 Micronized Anthracite

Figure 3.20 shows the relative sample burnout of Sample A1 and A2 in air. The reduction in particle size due to micronizing has dramatically improved the combustibility of the anthracite. Sample A1 did not burn at these conditions, with the maximum weight loss about equal to the volatile matter content of 8%. Sample A2 however achieved from 30 to 38% burnout. This observation of combustion of A2 was supported by the results of the flammability index tests, described in Section 3.4, where ignition of A2 was observed, but no ignition was observed for A1. This effect of improved anthracite combustibility with decreasing particle size agrees with conclusions reached by Beer (1969).

3.3.2 Blends of Anthracite and Thermal Coals

One purpose for studying the combustibility of blends was to look for interactions between the two coals during combustion. Figure 3.21 gives the results of EFC tests of mixtures of anthracite with the two thermal coals. Both figures are for combustion in air with the upper figure the results for a blend of Samples A1 and G and the bottom figure for a blend of Samples A1 and C. In both cases the blend was a 50% by weight of each sample. If the combustion properties of the two samples were simply additive with each coal particle burning with little interaction between particles, the burnout of the blend would fall midway between that of the original samples. At the longer residence times this appears to be true, with the burnout of the blend midway between that of the anthracite and that of the coal. However, at the shorter residence times the burnout of the mixture is less than that expected. Table 3.5 compares the measured burnout with the calculated burnout assuming additivity of burnout of the blend for mixtures MI and MIII. For residence times less than 0.3 s the burnout of Sample A1 in air was assumed to be zero.

3.3.3 Blends of Micronized Anthracite and Thermal Coals

Figure 3.22 gives the results of the EFC tests of mixtures of micronized anthracite and the two thermal coals for a blend of 50% A2 by weight and for a blend of 25% A2 and 75% thermal coal. The upper figure gives the results of blends of A2 with Sample G while the lower figure gives the results

of blends of A2 with Sample C. Table 3.5 compares the measured burnout of the blends MII, MIV, MV and MVI with the calculated burnout assuming additivity of burnout of the parent coals.

In contrast to the blends of anthracite discussed in Section 3.3.2, the blends of micronized anthracite and thermal coal appeared to burn as separate coals in the environment of the EFC tests. The measured burnout for all residence times could be predicted within 10% by simple summation of the burnout of the parent coals. No interaction in the blends to either improve or worsen the burnout of the blend was noted.

3.3.4 Beneficiated Product

Figure 3.23 gives the results of the EFC tests of the one beneficiated product (B1) submitted for combustion testing compared with the parent coal. The rate of burnout of both samples was extremely rapid. The burnout after only 0.12 s in air at 1100°C was greater than 95% daf for both samples. Within the accuracy of the EFC tests no difference in burnout rate was detected between the two samples.

3.4 Flammability Index

The furnace temperature at which the samples ignited in a pure oxygen atmosphere was measured within ±5°C according to the test procedure given in Section 2.4. This furnace temperature is the 'flammability index' given for the samples in Table 3.6.

Ignition occurs at the temperature and reactor conditions at which the rate of heat loss from the combusting particles is overbalanced by the rate of heat generation from the combustion reactions. Both the rate of heat loss and the rate of chemical reaction will be affected by furnace design, mixing, turbulence and other factors specific to the experimental apparatus. These factors may change drastically from reactor to reactor, thus the flammability index determined here is not a true ignition temperature and cannot be directly transferred to other equipment. However, the relative value of the flammability index will give an indication of the relative ease of ignition of the samples

tested. Several authors have used a flammability index test similar to that used here to gain such information (Nsakala et al., 1985, Douglas, 1980).

Typically at or above the flammability index temperature, a very distinct flame or 'explosion' was observed when the sample was injected into the reactor tube. However, for the two anthracite samples and their mixtures with sample G, sparks from the ignition of a few individual particles were observed at temperatures from 50 to 100°C below the flammability index. The flammability index of sample A1 was 650°C. The micronized anthracite, sample A2, had a flammability index of 566°C, showing an improvement of ignition characteristics with the decreased particle size. The high concentration of very small particles in sample A2 and the associated more rapid combustion rate of these small particles has contributed to the more rapid ignition.

Both of the coal samples G and C gave a distinct 'explosion'. Sample C gave the lower temperature (401°C), with sample G a temperature of 483°C. These flammability indexes were more than 80°C less than the micronized anthracite, emphasizing the relatively poor ignitability of anthracite.

The flammability indexes of the mixtures of anthracite and coals C and G (MI to MIV) were observed to be between those of the unblended samples. Table 3.6 includes a calculated flammability index for the mixtures, which is simply the average of the index for samples A1, A2 and C and A1, A2 and G. For mixtures MI, MII and MIII the observed temperatures were lower than the calculated, suggesting a possible interaction of the thermal coal and the anthracite during ignition in this test.

The flammability index of sample O and the beneficiated product sample B1 were similar (457°C and 448°C). The lower temperature for sample B1 may indicate an improvement in ignition properties, but this should be confirmed by further testing.

4. CONCLUSIONS

Entrained flow combustion tests and flammability index measurements were used to evaluate the combustibility of three thermal coals, an anthracite, a micronized anthracite, blends of thermal coal and anthracite and a beneficiated coal product. In addition, the TGA pyrolysis and combustion profile and the DSC combustion profile were determined for one thermal coal and a beneficiated product made from that coal.

The following conclusions were drawn from the results of this work:

1. The ranking of the samples in order of increasing rate of carbon burnout was A1<G<C<O, corresponding to increasing combustion reactivity with decreasing rank.

2. The results from the EFC tests indicated that under the conditions studied the pulverized anthracite probably did not ignite.

3. Micronized anthracite had dramatically improved ignition and burnout properties over the pulverized anthracite, but was still not as reactive as the thermal coals.

4. Blending pulverized anthracite with thermal coal appeared to give lower carbon burnout than expected at the shorter residence times during the entrained flow combustion tests.

5. The thermal coal and micronized anthracite appeared to burn in the EFC tests independently when blended. The burnout of the blend could be predicted by summing the burnout of the individual samples times the fraction in the blend.

6. Three of the blends of anthracite and thermal coal gave flammability indexes lower than expected. The thermal coal may be enhancing the ignition properties as measured by this test.

7. The combustibility of the beneficiated sample, as determined by TGA, DSC, EFC and flammability index tests, was the same as the parent coal.

5. RECOMMENDATIONS

Although the results of the combustion tests summarized in this report indicate little or no interaction of blended samples these results must be interpreted with caution. The entrained flow combustion experimental conditions were similar to those anticipated in a typical pulverized coal flame in that pulverized samples were suspended in air and rapidly heated. However the conditions of this small scale test were different in several manners. The large amount of excess air used would minimize the interaction of individual particles in the mixtures of dissimilar coals tested. Combustion experiments on equipment that establishes a high temperature flame region and a char burnout zone are recommended to confirm the conclusions drawn from this study. This would require experiments at a larger scale with the associated increase in sample size required and cost per experiment.

The initial test results given in this report indicate that the beneficiated product has combustion characteristics similar to the original coal. This should be confirmed on larger scale combustion equipment. Other combustibility parameters that should be tested include flame stability, pollutant emissions, slagging and fouling properties of the ash, unburnt carbon in flyash and electrostatic precipitator properties of the flyash.

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Table 2.1 Labelling of Test Samples

Sample Label	Description
A1	Mount Klappan
A2	Micronized Anthracite
C	Coal Valley HV Bituminous
G	Goodrich LV Bituminous
O	Obed Mountain HV Bituminous
B1	Beneficiated Obed Mountain

Table 2.2 Portion of Sample in -200 Mesh Fraction as Received from Gulf Canada

	+200 mesh	-200 mesh
A1	61%	39%
A2	--	100
G	24	76
C	33	67
O	100	--
B1	100	--

Table 3.1 Ultimate and Proximate Analyses of Test Samples

	Sample*					
	A1	A2	G	C	O	B1
Ultimate (daf)						
C	92.2	91.9	86.2	77.7	76.5	77.9
H	2.4	2.4	4.3	4.4	5.2	4.9
N	1.4	1.4	1.6	1.2	1.7	1.8
S	0.6	0.5	0.3	0.3	0.8	1.0
O (diff)	3.4	3.8	7.6	16.4	15.8	14.4
Proximate						
(Moisture)	2.5	2.9	2.0	8.2	11.2	1.5
Ash (dry)	11.2	10.5	11.7	11.1	14.9	13.7
VM (daf)	8.1	9.0	25.1	36.2	43.6	39.1
FC (daf)	91.9	91.0	74.9	63.8	56.4	60.9

* See Table 2.1 for sample identification .

Table 3.2 Mass Median Particle Size of -200 Mesh Fraction Used in Combustion Tests

Sample	Mass Median size (μm)
A1	35.3
A2	16.1
G	30.9
C	35.2
O	43.7
B1	39.9

Table 3.3 Blends Prepared for Combustibility Tests

Sample	Weight % as Received
MI	50 A1: 50 C
MII	50 A2: 50 C
MIII	50 A1: 50 G
MIV	50 A2: 50 G
MV	25 A2: 75 C
MVI	25 A2: 75 G

Table 3.4 Summary of EFC Tests for All Samples

Sample	Reactor Length (cm)	Residence Time (s)	% 02	Burnout (wt% daf)
A1	30	0.30	21	0.9
	35	0.36	"	9.1
A2	20	0.18	21	20.1
	25	0.24	"	31.3
	30	0.30	"	37.7
	35	0.36	"	35.6
C	15	0.12	5	45.2
	20	0.18	"	42.5
	25	0.24	"	54.6
	15	0.12	21	91.9
	20	0.18	"	91.0
	25	0.24	"	96.4
	30	0.30	"	93.7
G	15	0.12	5	30.4
	20	0.18	"	30.4
	25	0.24	"	34.4
	30	0.30	"	33.6
	15	0.12	21	44.0
	20	0.18	"	47.2
	20	0.18	"	44.0*
	20	0.18	"	34.1*
	25	0.24	"	52.5
	30	0.30	"	57.8
MI	20	0.18	5	3.9
	25	0.24	"	16.2
	30	0.30	"	25.7
	20	0.18	21	19.3
	25	0.24	"	37.4
	30	0.30	"	41.6
MII	20	0.18	5	26.3
	25	0.24	"	28.8
	30	0.30	"	34.9
	20	0.18	21	57.1
	20	0.18	"	60.7*
	25	0.24	"	65.3
	30	0.30	"	63.3

* Repeat experiments

MIII	20	0.18	5	0.0
	25	0.24	"	0.0
	30	0.30	"	9.8
	35	0.36	"	16.8
	20	0.18	21	0.0
	25	0.24	"	13.3
	30	0.30	"	25.0
	35	0.36	"	39.6
MIV	25	0.24	5	19.0
	30	0.30	"	22.5
	35	0.36	"	22.5
	20	0.18	21	36.0
	25	0.24	"	40.8
	30	0.30	"	47.7
	35	0.36	"	52.5
MV	15	0.12	21	75.5
	20	0.18	"	79.5
	25	0.24	"	80.8
	30	0.30	"	80.9
MVI	15	0.12	21	30.8
	20	0.18	"	42.2
	25	0.24	"	48.7
	30	0.30	"	52.8
0	15	0.12	21	97.1
	20	0.18	"	98.3
	25	0.24	"	99.2
B1	15	0.12	21	96.4
	20	0.18	"	98.7
	25	0.24	"	99.2

Table 3.5 Calculated Burnout of Mixtures (21% Oxygen)

Sample	Residence Time (s)	Measured Burnout (wt% daf)	Calculated Burnout (wt% daf)
MI	0.18	19.3	45.5
50 A1: 50 C	0.24	37.4	48.2
	0.30	41.6	47.3
MII	0.18	57.1	55.6
50 A2: 50 C	0.24	65.3	63.9
	0.30	63.3	64.7
MIII	0.18	0.0	23.6
50 A1: 50 G	0.24	13.3	26.2
	0.30	25.0	29.4
MIV	0.18	36.0	33.7
50 A2: 50 G	0.24	40.8	41.9
	0.30	47.7	47.8
MV	0.18	79.5	73.3
25 A2: 75 C	0.24	80.8	80.1
	0.30	80.9	79.7
MVI	0.18	42.2	38.0
25 A2: 75 G	0.24	48.7	47.2
	0.30	52.8	52.8

Table 3.6 Flammability Indexes for -200 Mesh Fractions of All Samples

Sample	Flammability Index (°C)	Calculated Flammability Index (°C)
A1	550*-650	
A2	497* - 566	
G	483	
C	401	
O	457	
B1	448	
MI	480	526
MII	475	484
MIII	486* - 535	567
MIV	490* - 535	525

* 'Sparking' observed with no flame

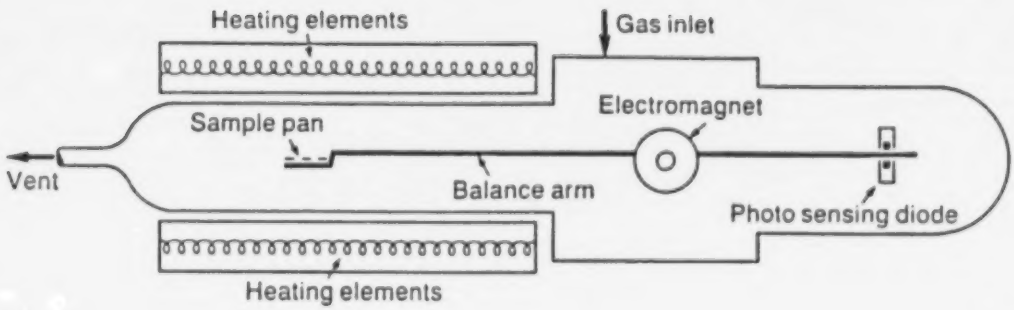


Figure 2.1 Schematic of the Thermogravimetric Analyzer (TGA) and Differential Scanning Calorimeter (DSC)

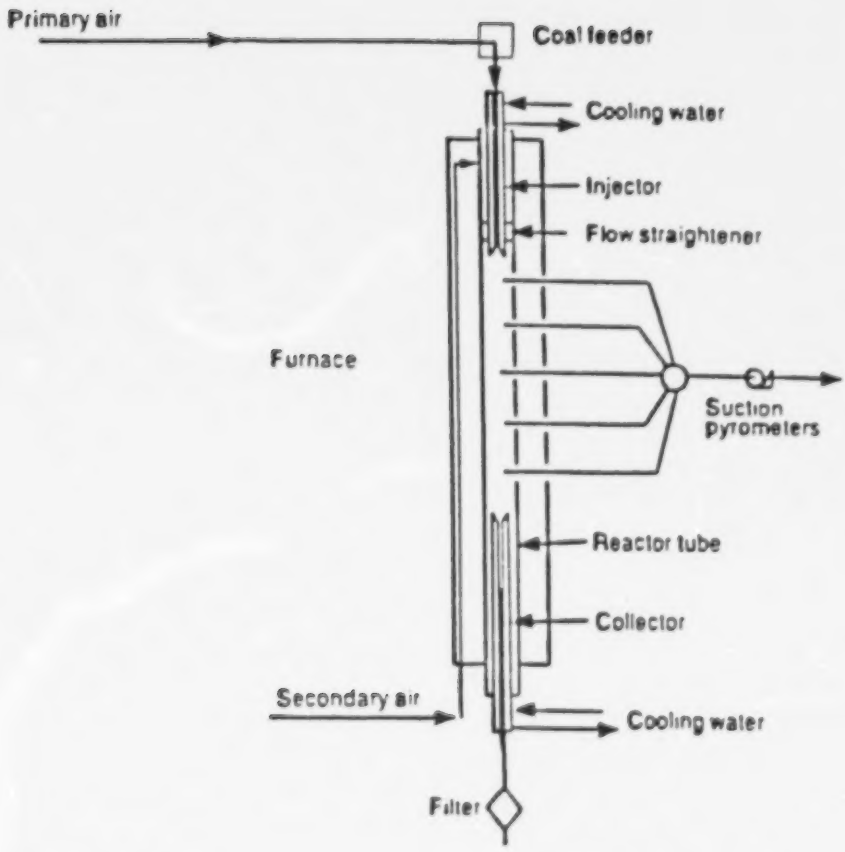


Figure 2.2 Schematic of the Entrained Flow Combustor (EFC)

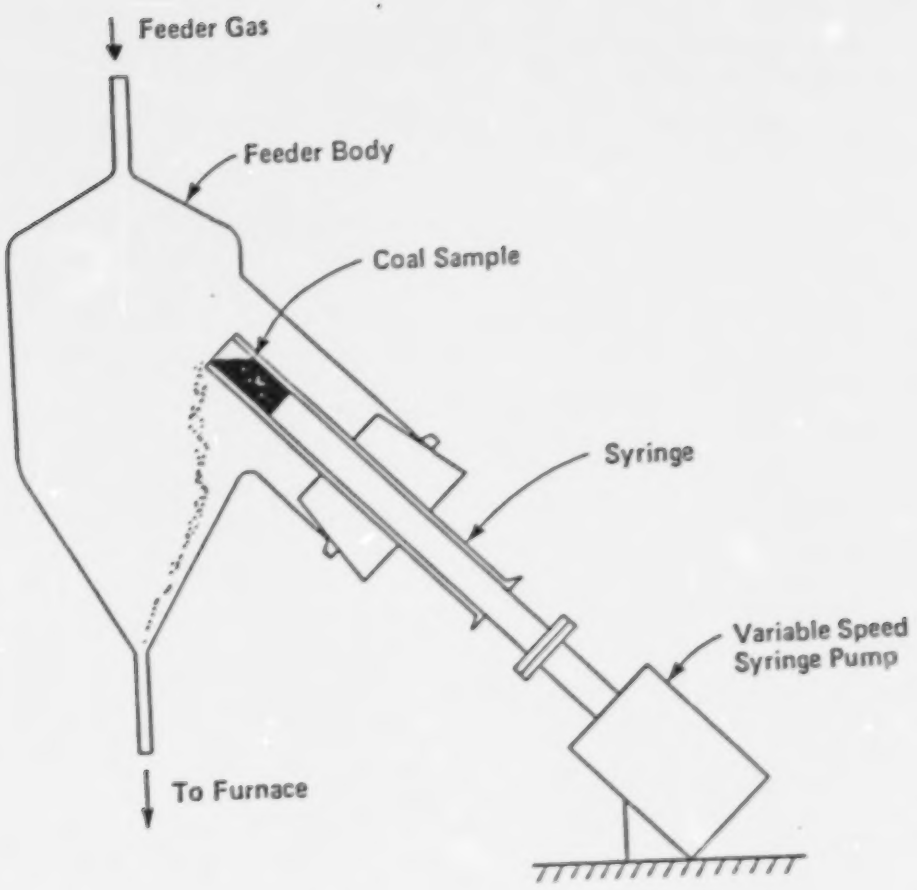


Figure 2.3 Schematic of the EFC Coal Feeder

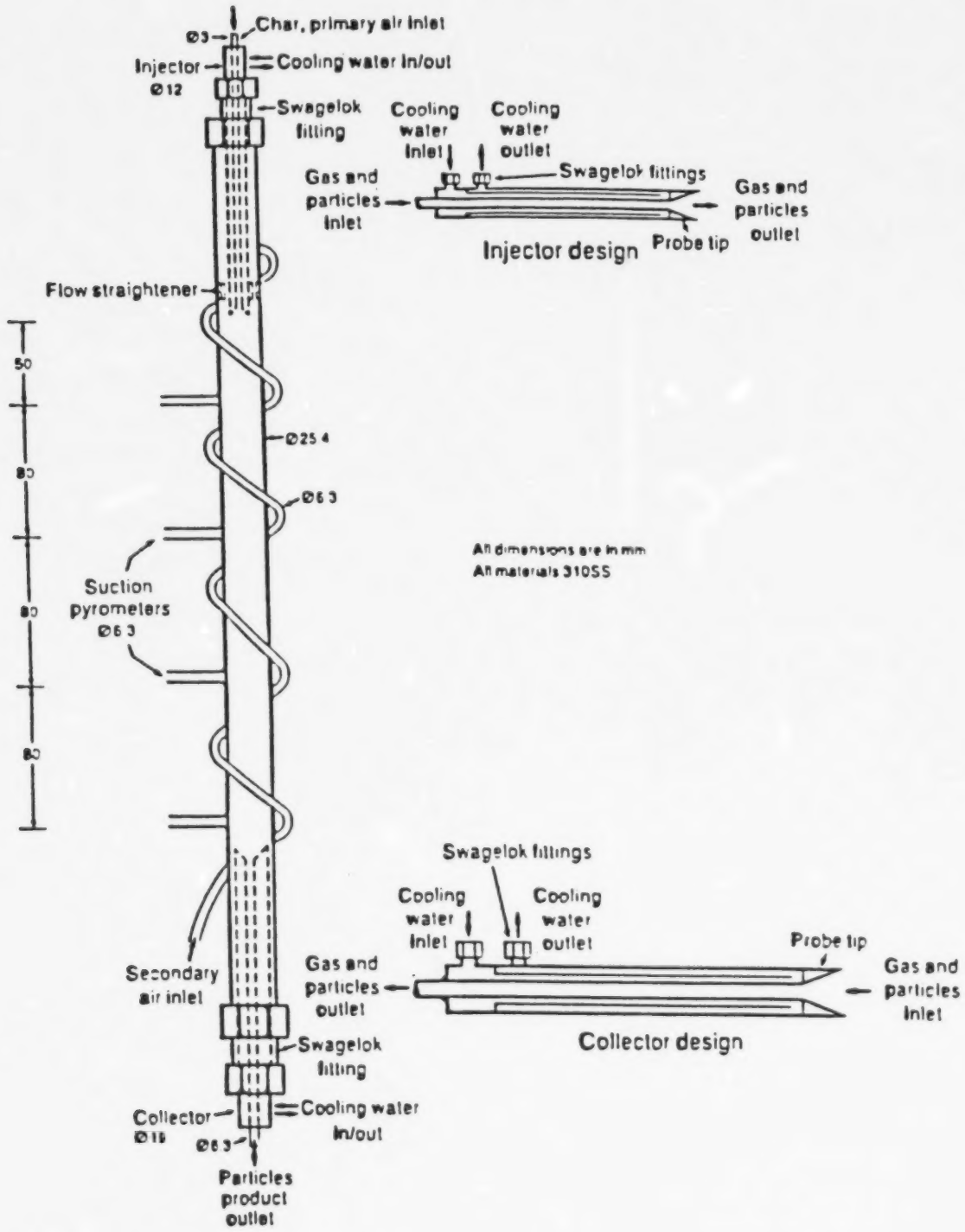


Figure 2.4 Detailed Schematic of the EFC Reactor

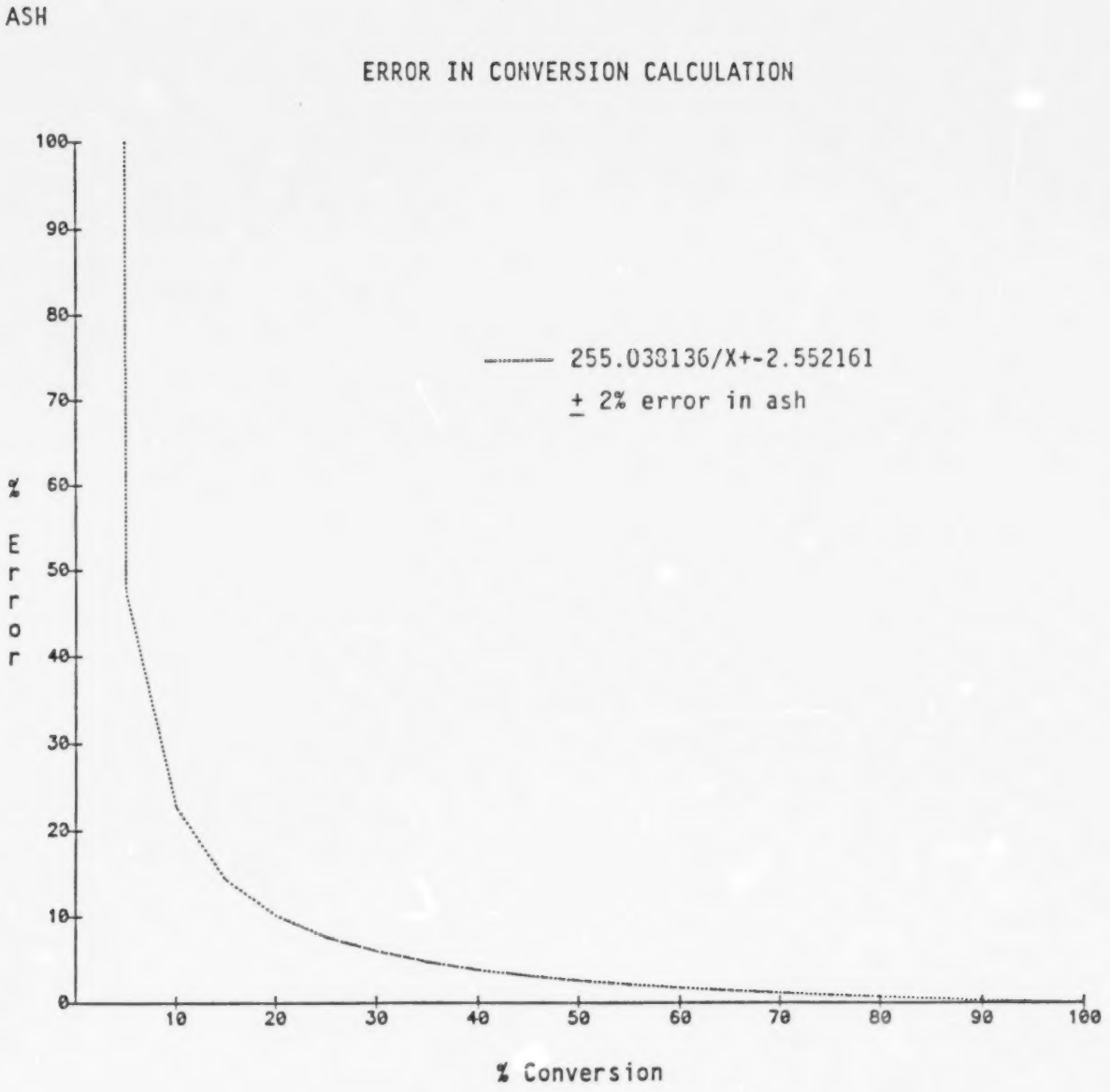


Figure 2.5 Effect of Error in Ash Determination on Calculated Burnout

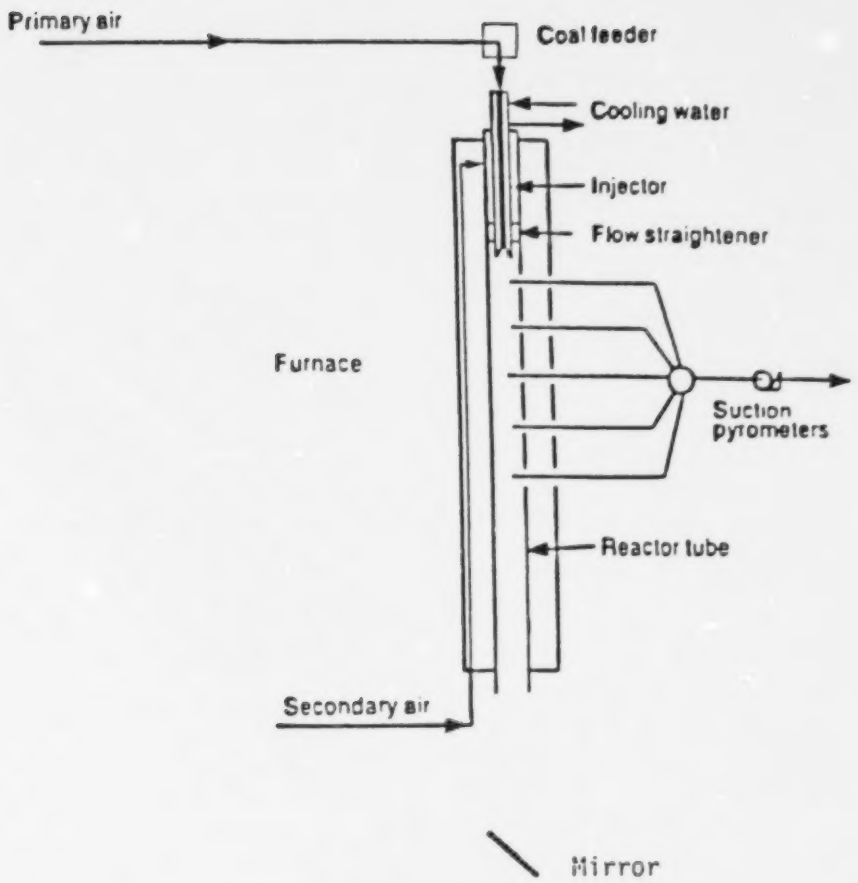


Figure 2.6 Schematic of the EFC - Set Up for Flammability Index Tests

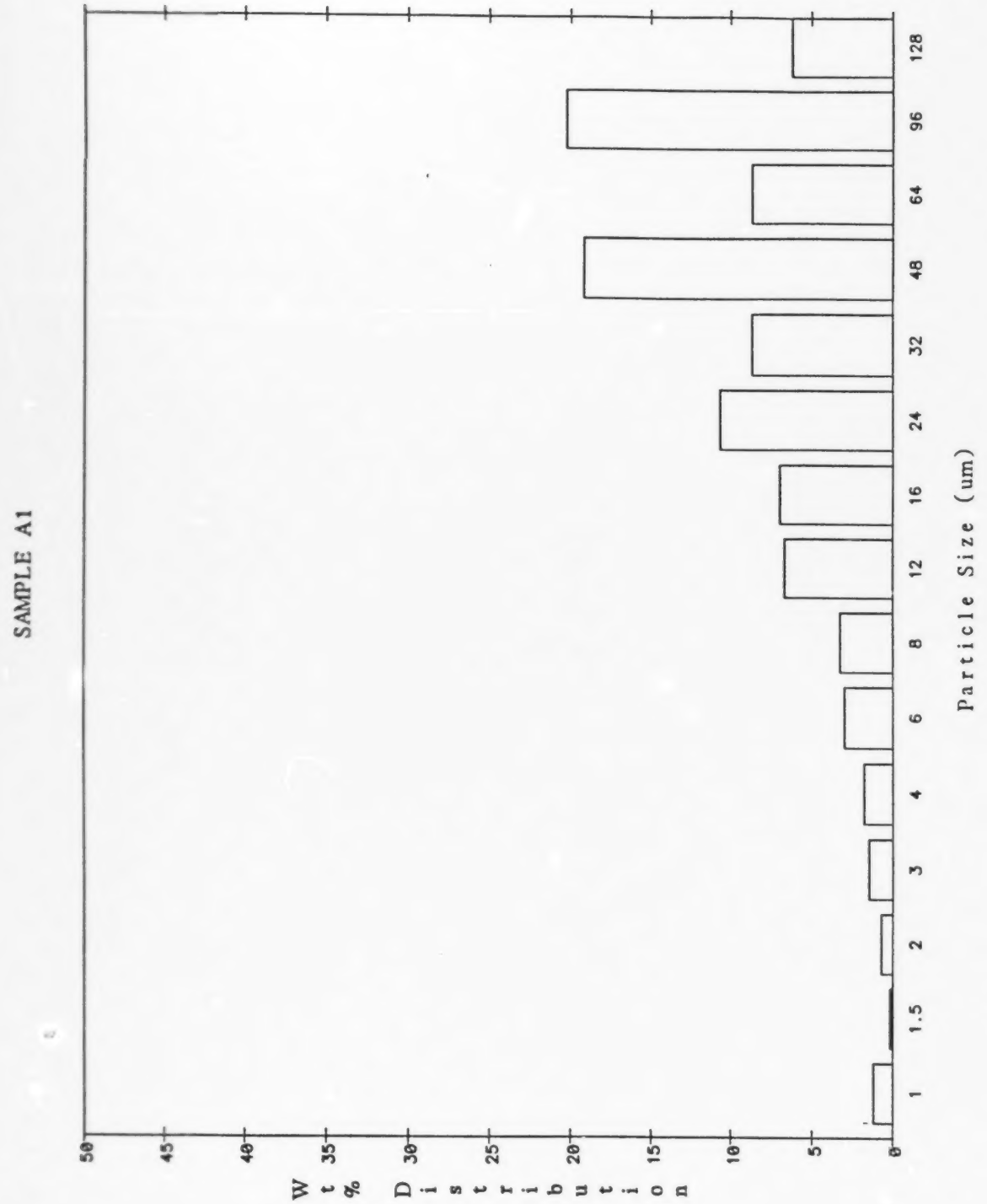


Figure 3.1 Particle Size Distribution of Sample A1

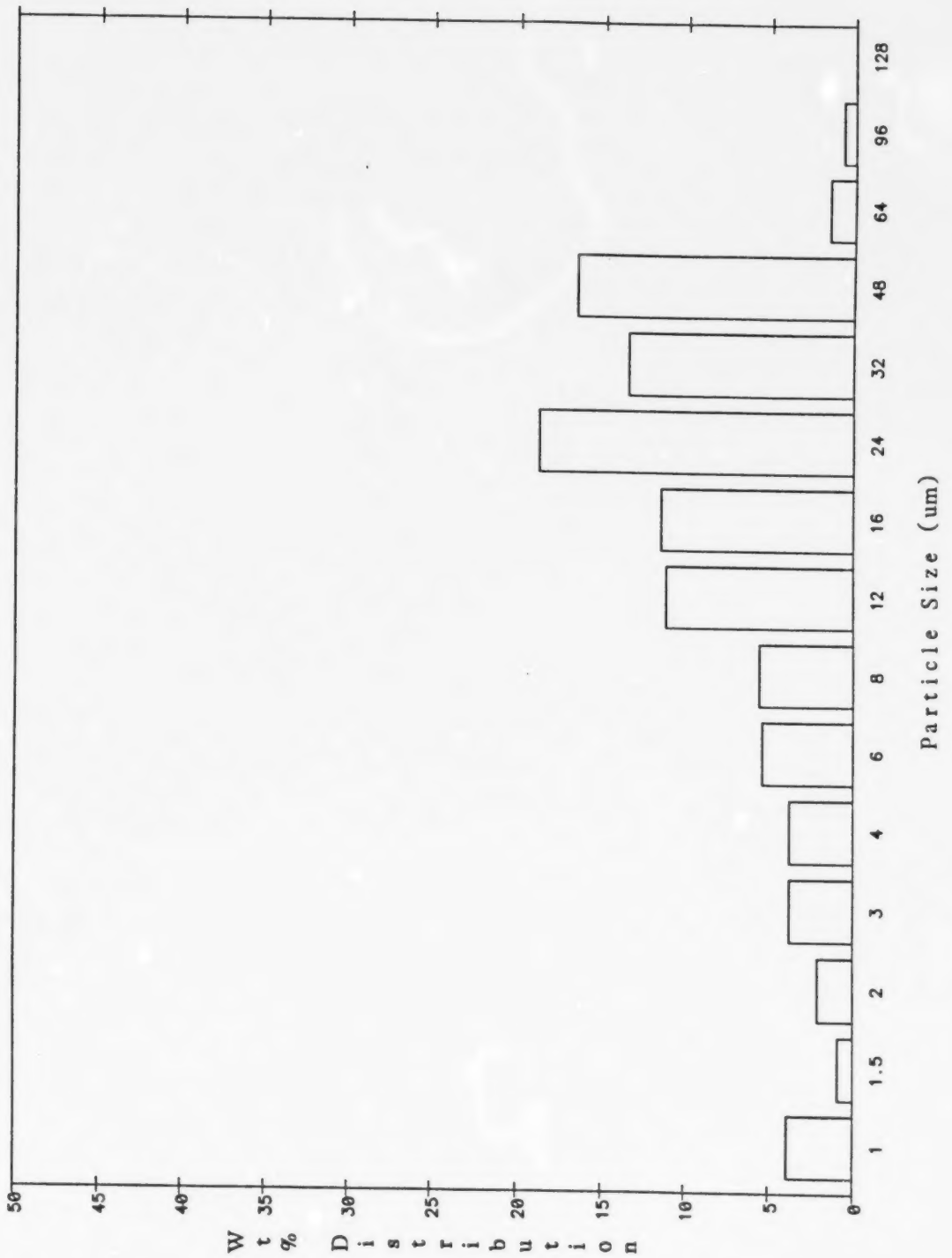


Figure 3.2 Particle Size Distribution of Sample A2

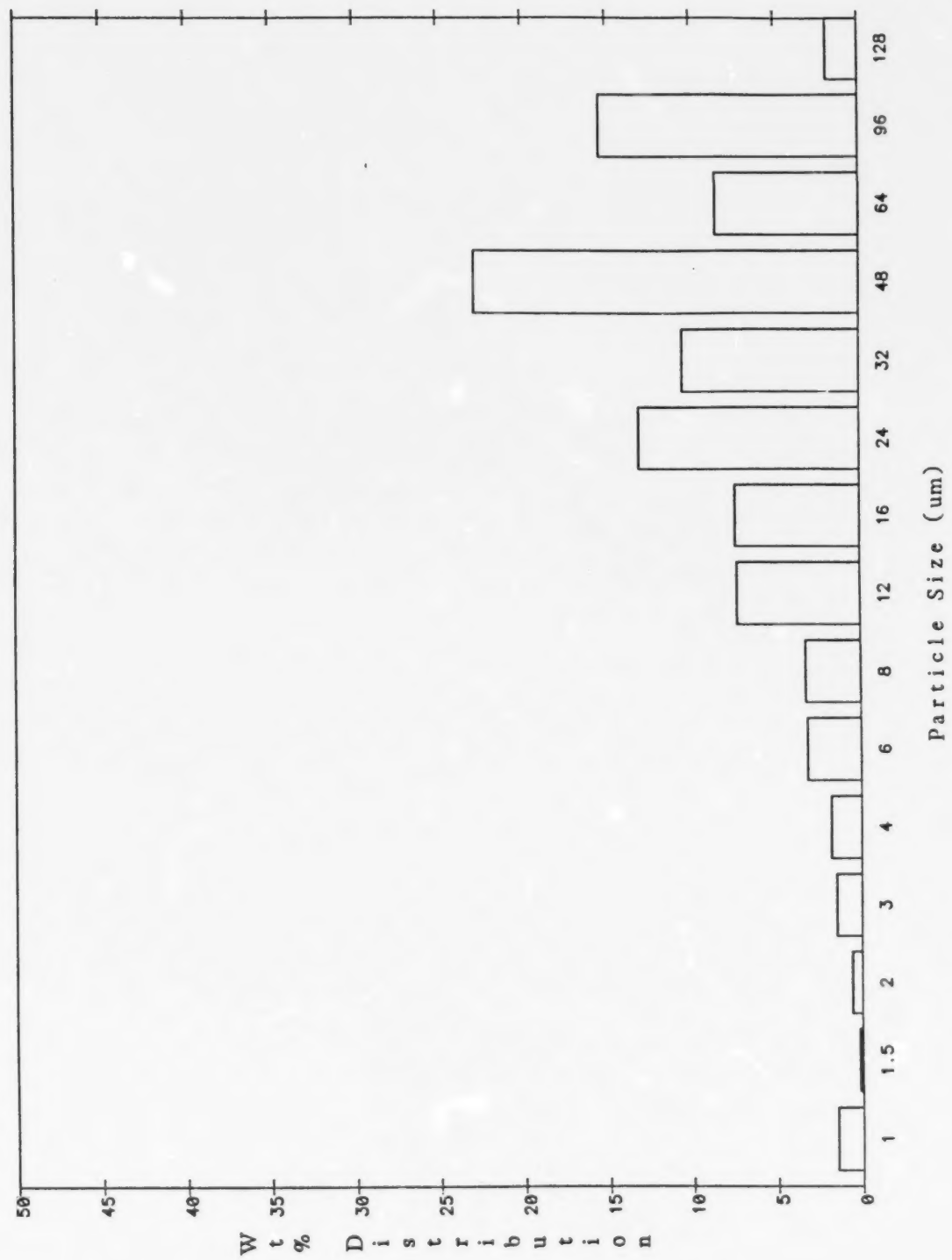


Figure 3.3 Particle Size Distribution of Sample G

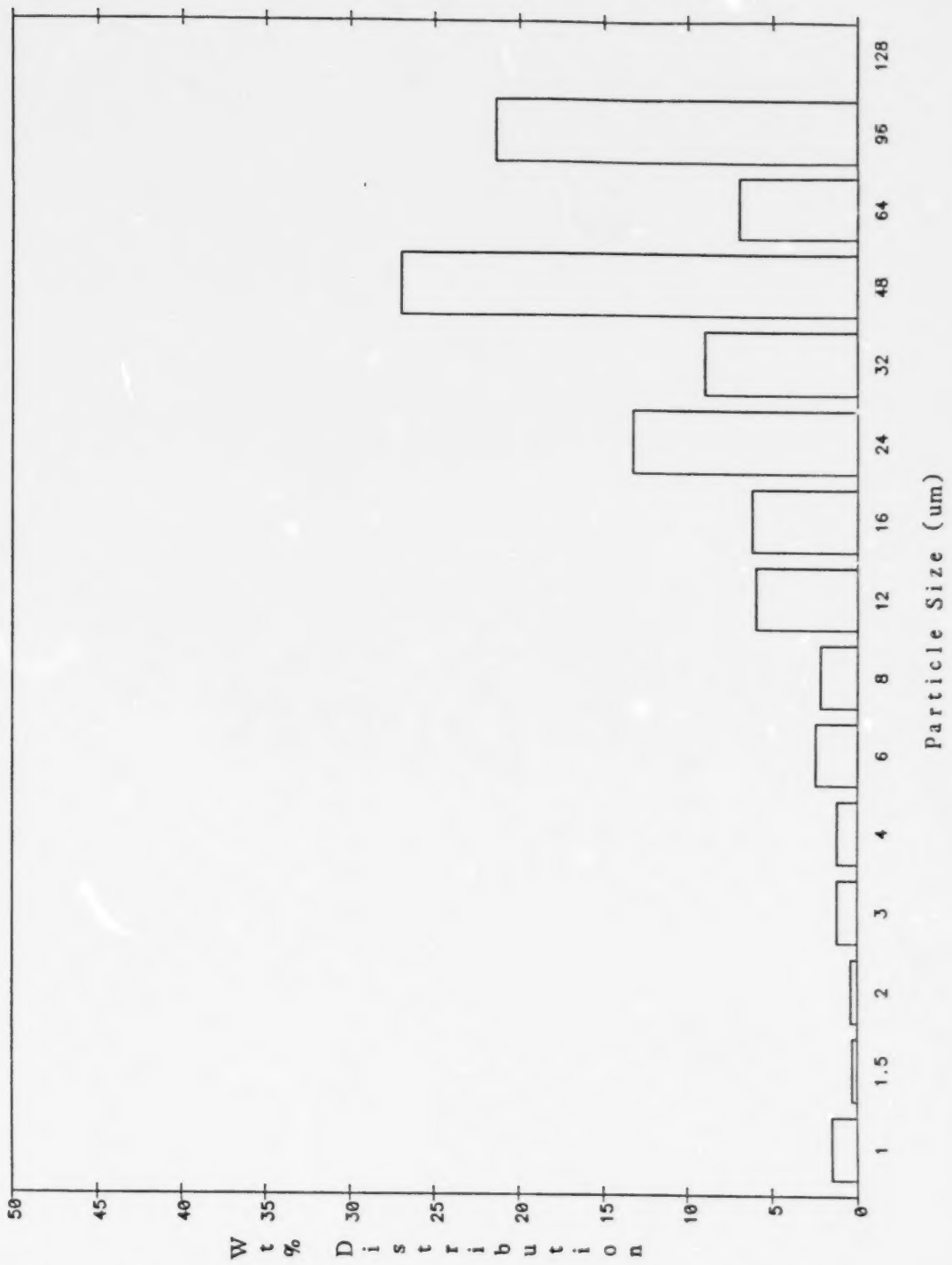


Figure 3.4 Particle Size Distribution of Sample C

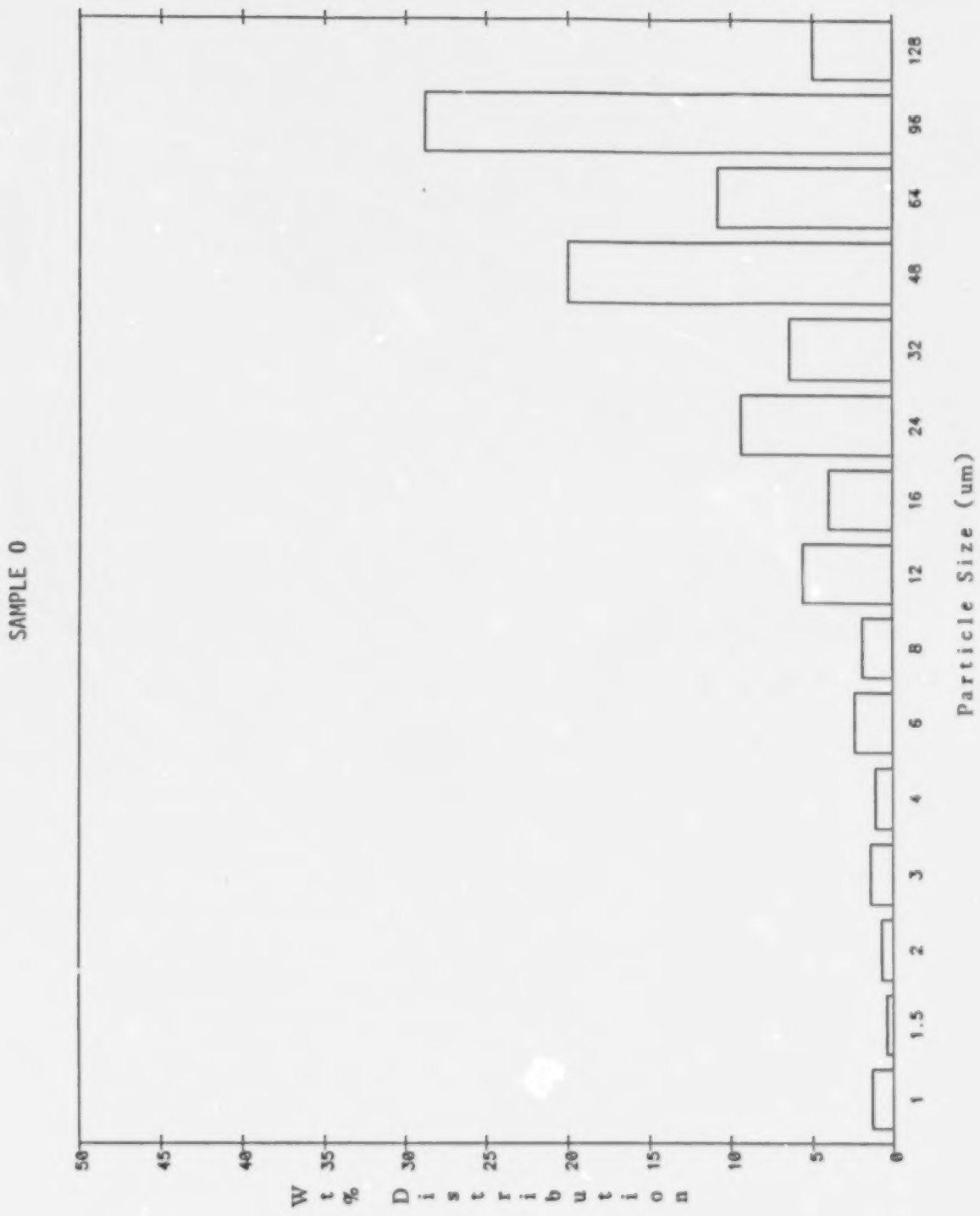


Figure 3.5 Particle Size Distribution of Sample 0

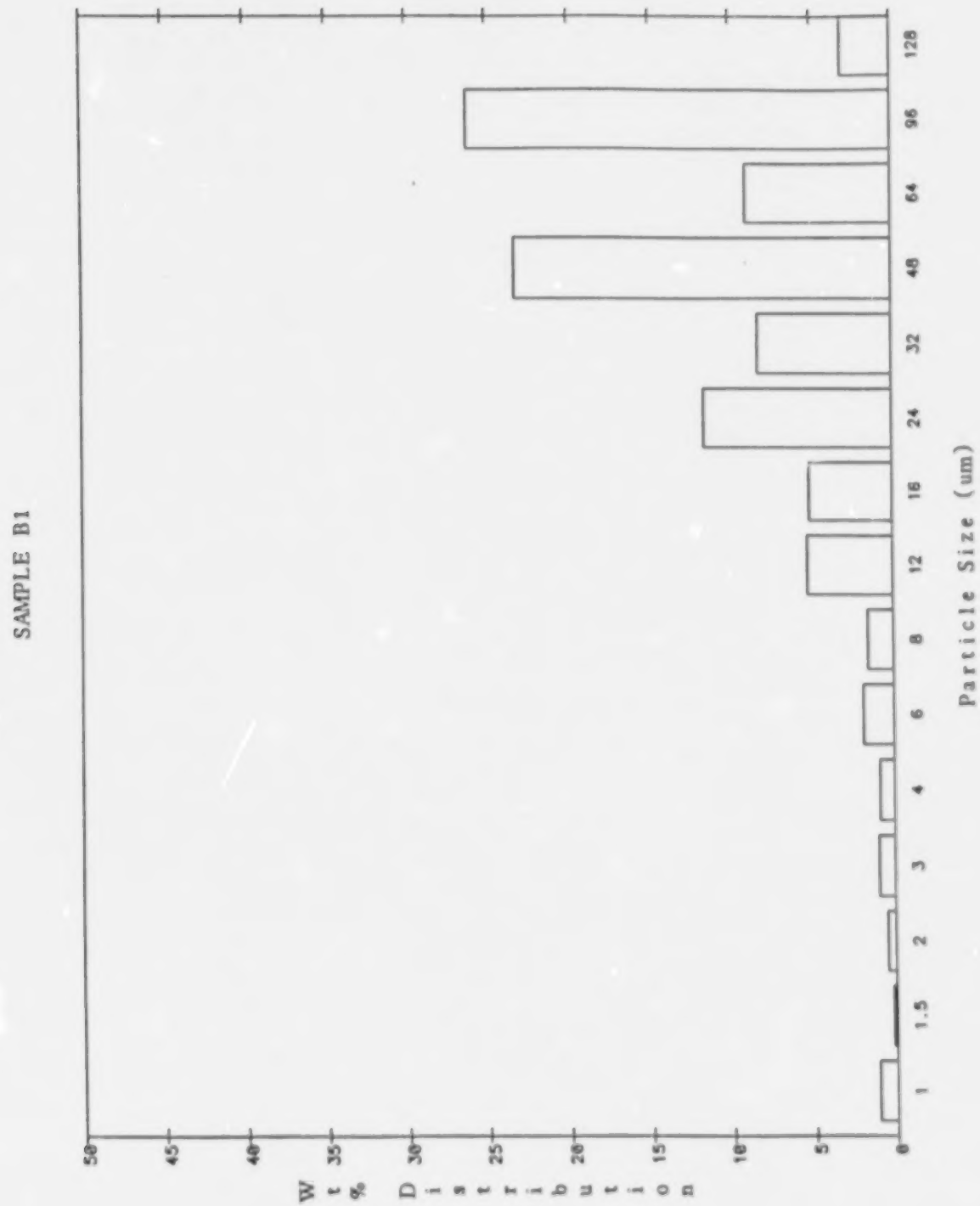


Figure 3.6 Particle Size Distribution of Sample B1

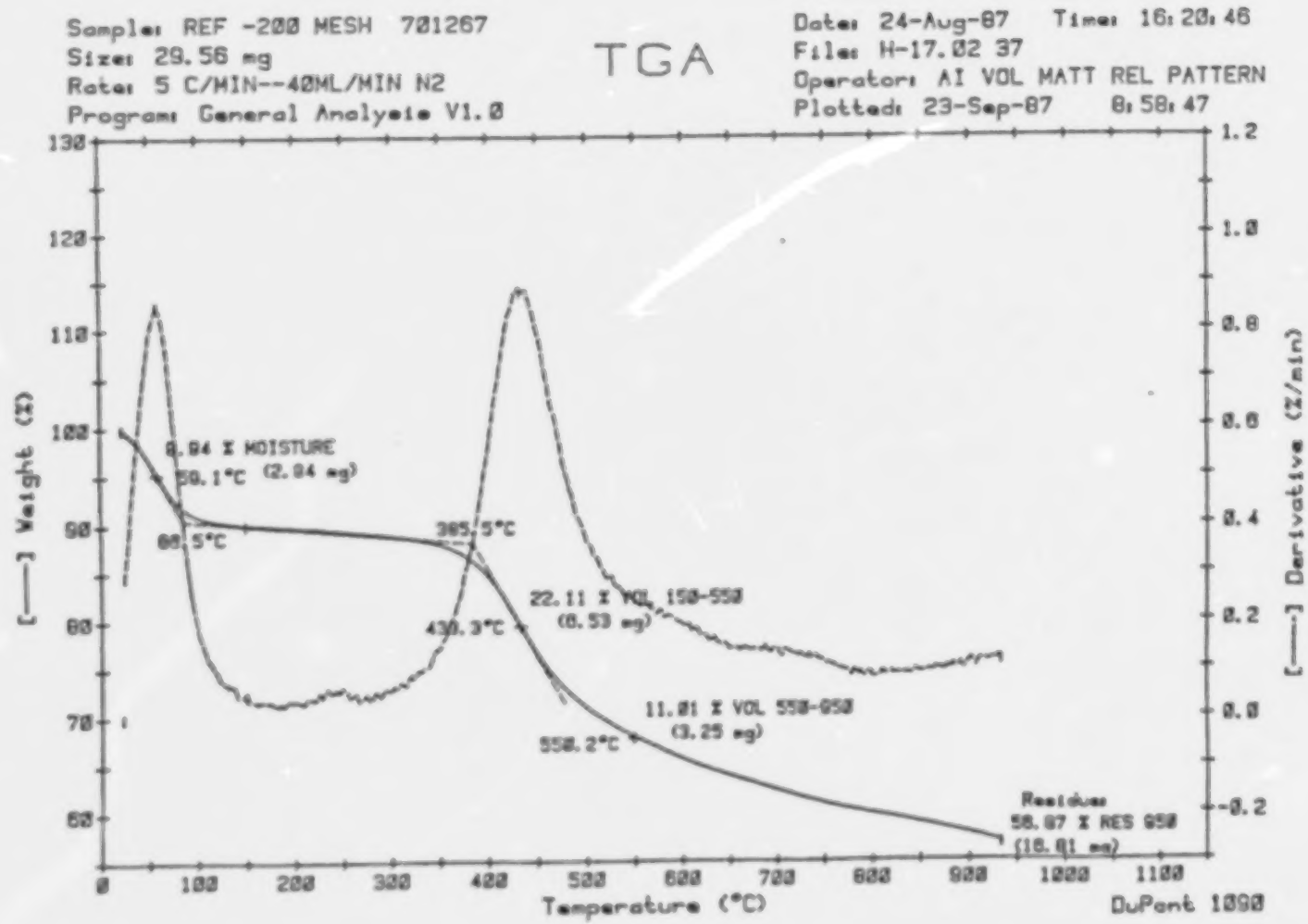


Figure 3.7 TGA Pyrolysis Profile for Sample 0

Sample: REF -200 MESH 701267
Size: 29.56 mg
Rate: 5 C/MIN--40ML/MIN N2
Program: TGA Analysis V2.0

Date: 24-Aug-87 Time: 16:20:46
File: H-17.02 37
Operator: AI VOL MATT REL PATTERN
Plotted: 23-Sep-87 8:51:50

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		59.1	86.5	2.94	9.94
VOL 150-550	385.5	433.3		6.53	22.11
VOL 550-950		550.2		3.25	11.01
RES 950		Residue at 933.7 °C		16.81	56.87

Modified Sample Weight: 29.56 mg

Figure 3.8 TGA Pyrolysis Profile Temperatures for Sample U

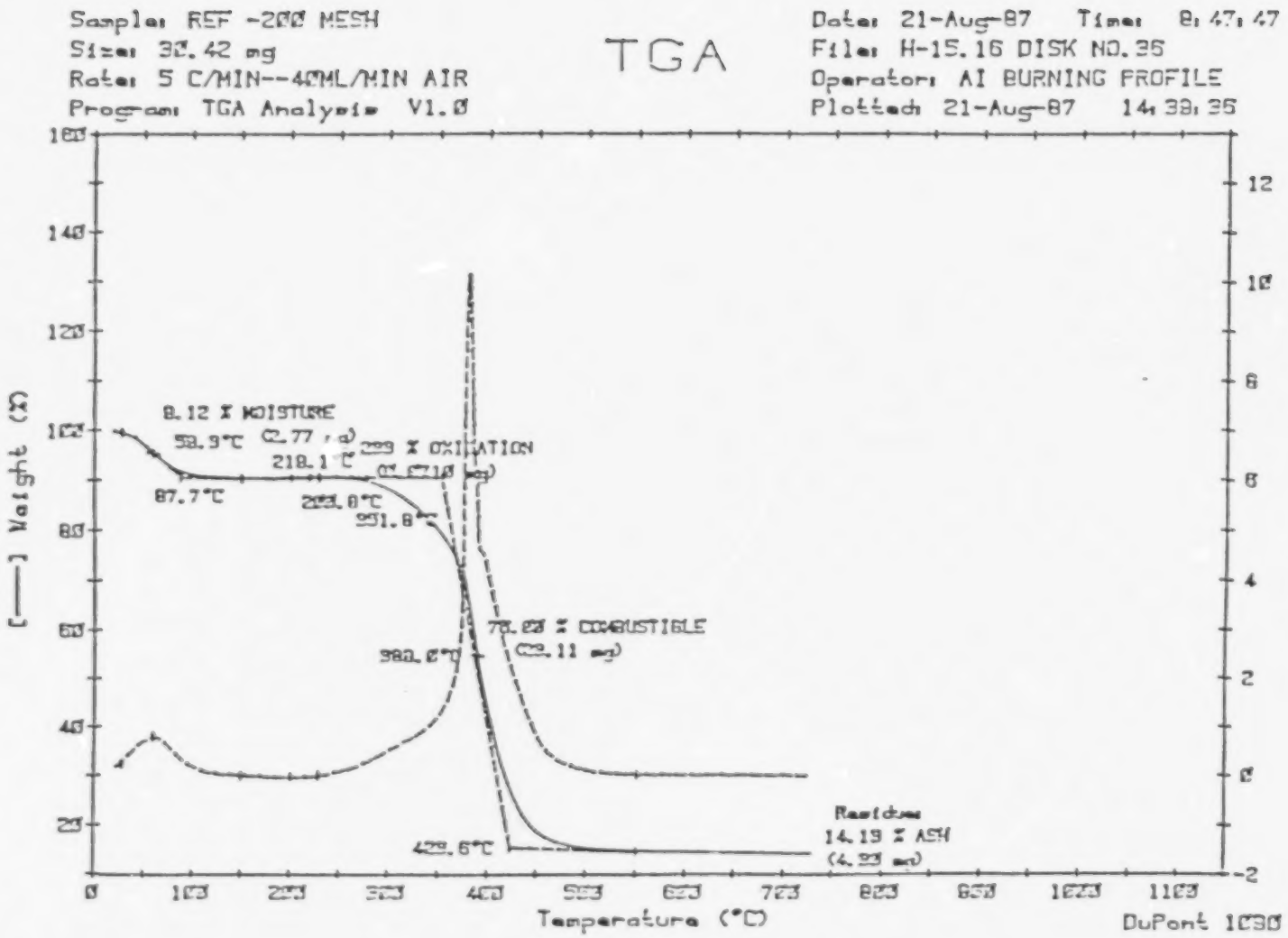


Figure 3.9 TGA Combustion Profile for Sample 0

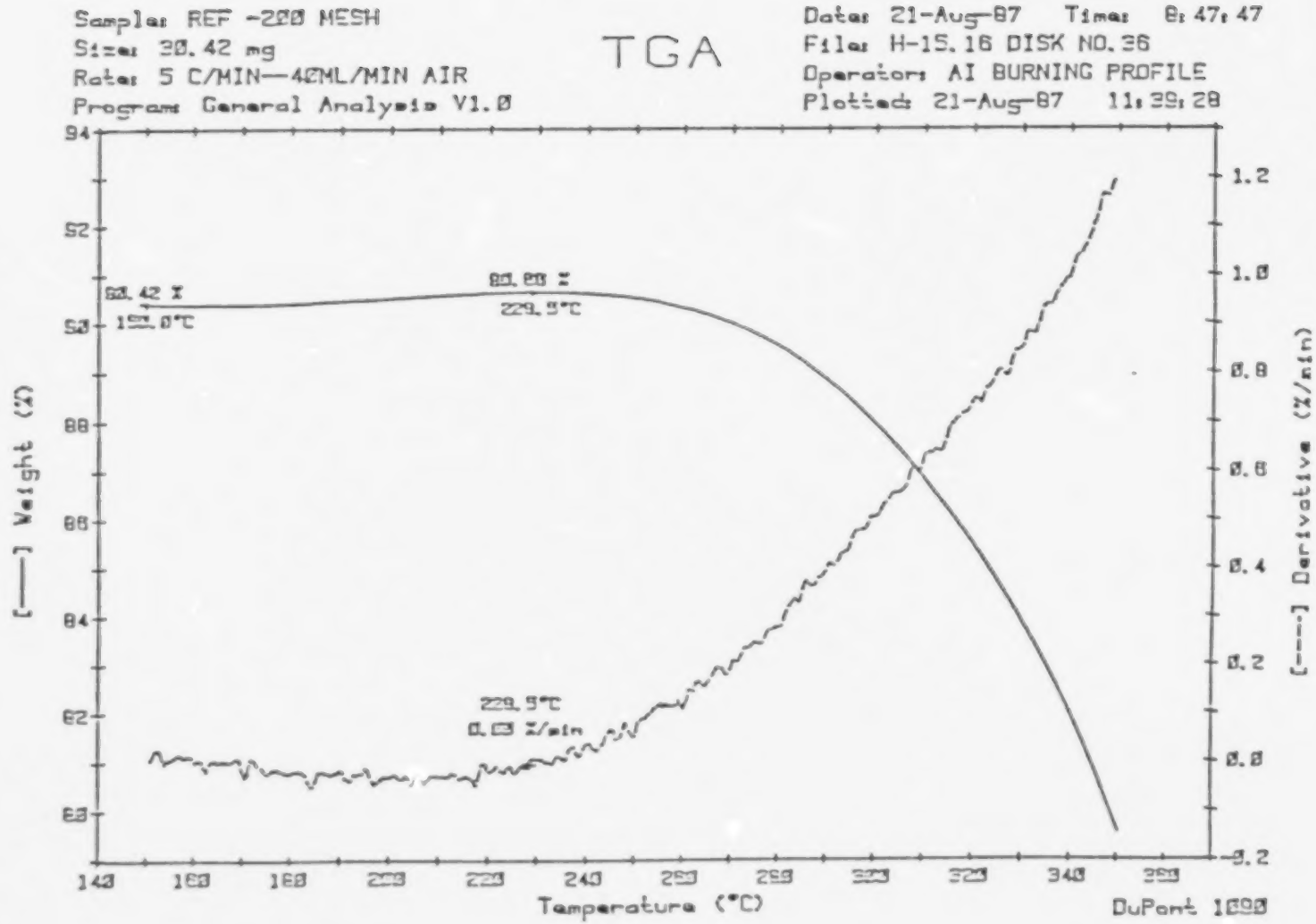


Figure 3.10 TGA Ignition Temperature for Sample O

Sample: REF -200 MESH
Size: 30.42 mg
Rate: 5 C/MIN--40ML/MIN AIR
Program: TGA Analysis V1.0

Date: 21-Aug-87 Time: 8:47:47
File: H-15.16 DISK NO.38
Operator: AI BURNING PROFILE
Plotted: 21-Aug-87 15:05:45

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		58.3	87.7	2.77	8.12
OXIDATION		200.8	218.1	(0.07)	(0.23)
COMBUSTIBLE	351.8	389.0	423.8	23.11	76.00
ASH	Residue at 732.8 °C			4.30	14.13

Modified Sample Weight: 30.41 mg

Figure 3.11 TGA Combustion Profile Temperatures for Sample 0

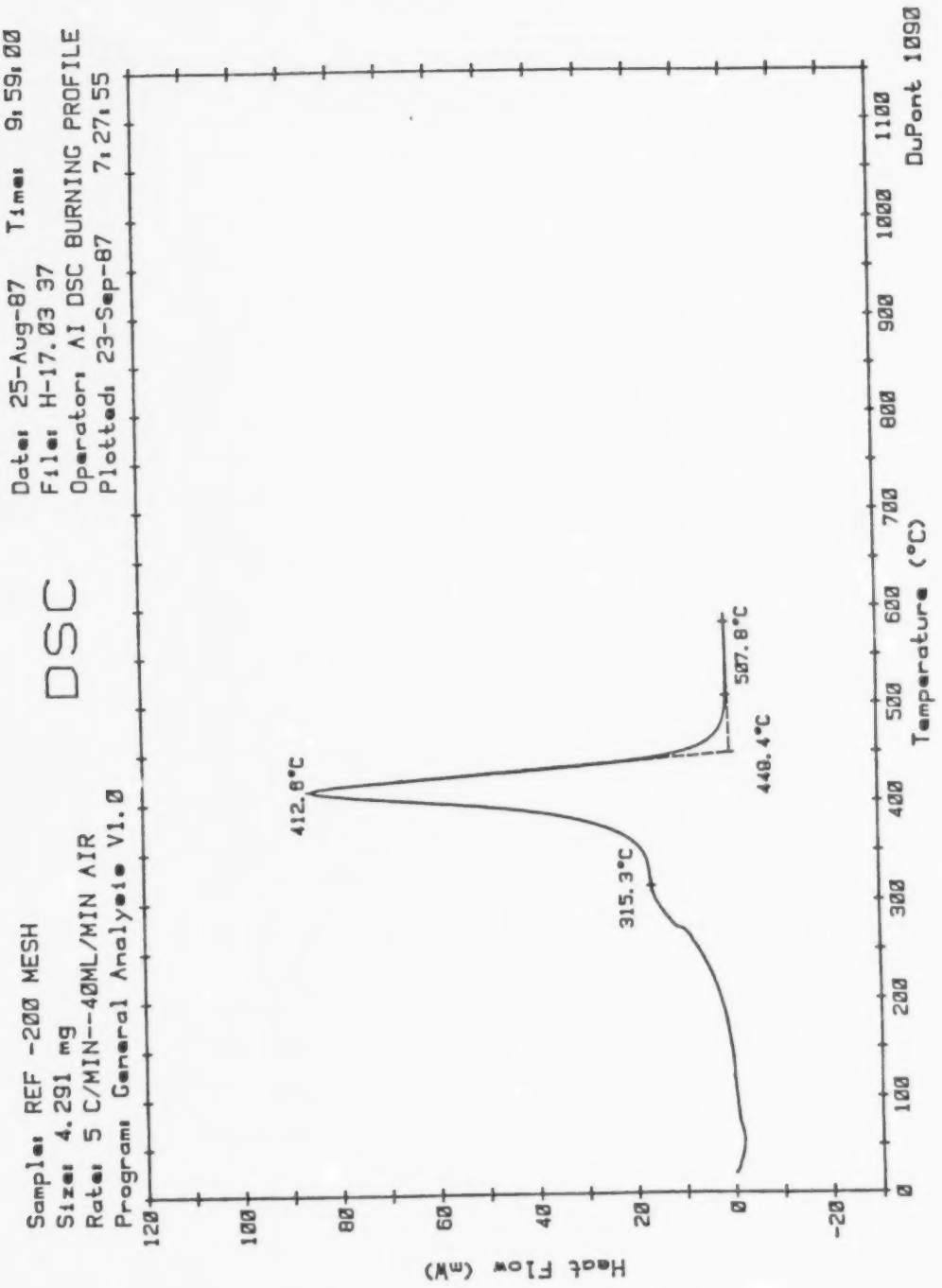


Figure 3.12 DSC Profile for Sample 0

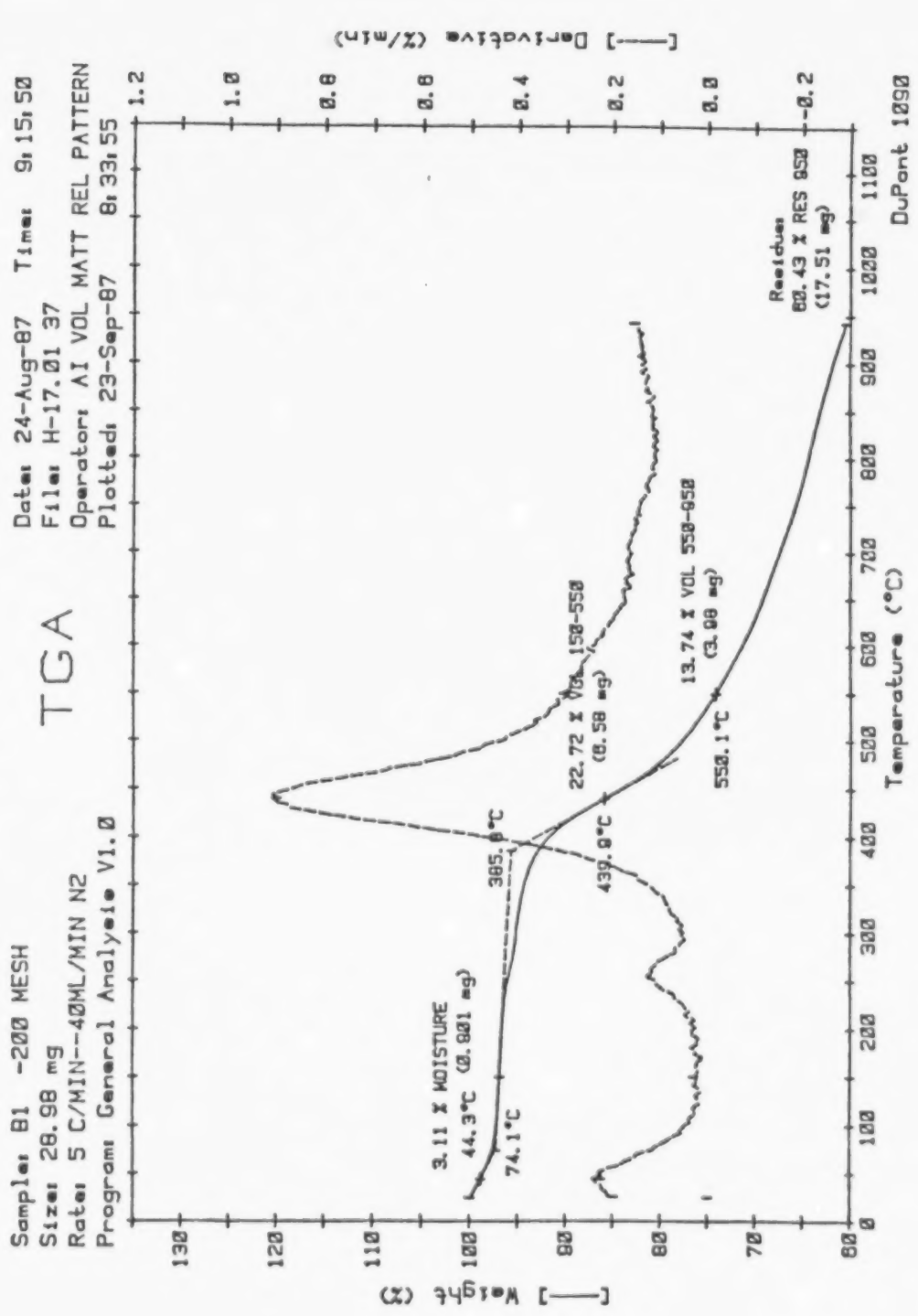


Figure 3.13 TGA Pyrolysis Profile for Sample B1

Sample: B1 -200 MESH
Size: 28.98 mg
Rate: 5 C/MIN--40ML/MIN N2
Program: TGA Analysis V2.0

Date: 24-Aug-87 Time: 9:15:50
File: H-17.01 37
Operator: AI VOL MATT REL PATTERN
Plotted: 23-Sep-87 8:43:42

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		44.3	74.1	0.90	3.11
VOL 150-550	385.8	439.9		6.58	22.72
VOL 550-950		550.1		3.98	13.74
RES 950		Residue at 942.1 °C		17.51	60.43

Modified Sample Weight: 28.97 mg

Figure 3.14 TGA Pyrolysis Profile Temperatures for Sample B1

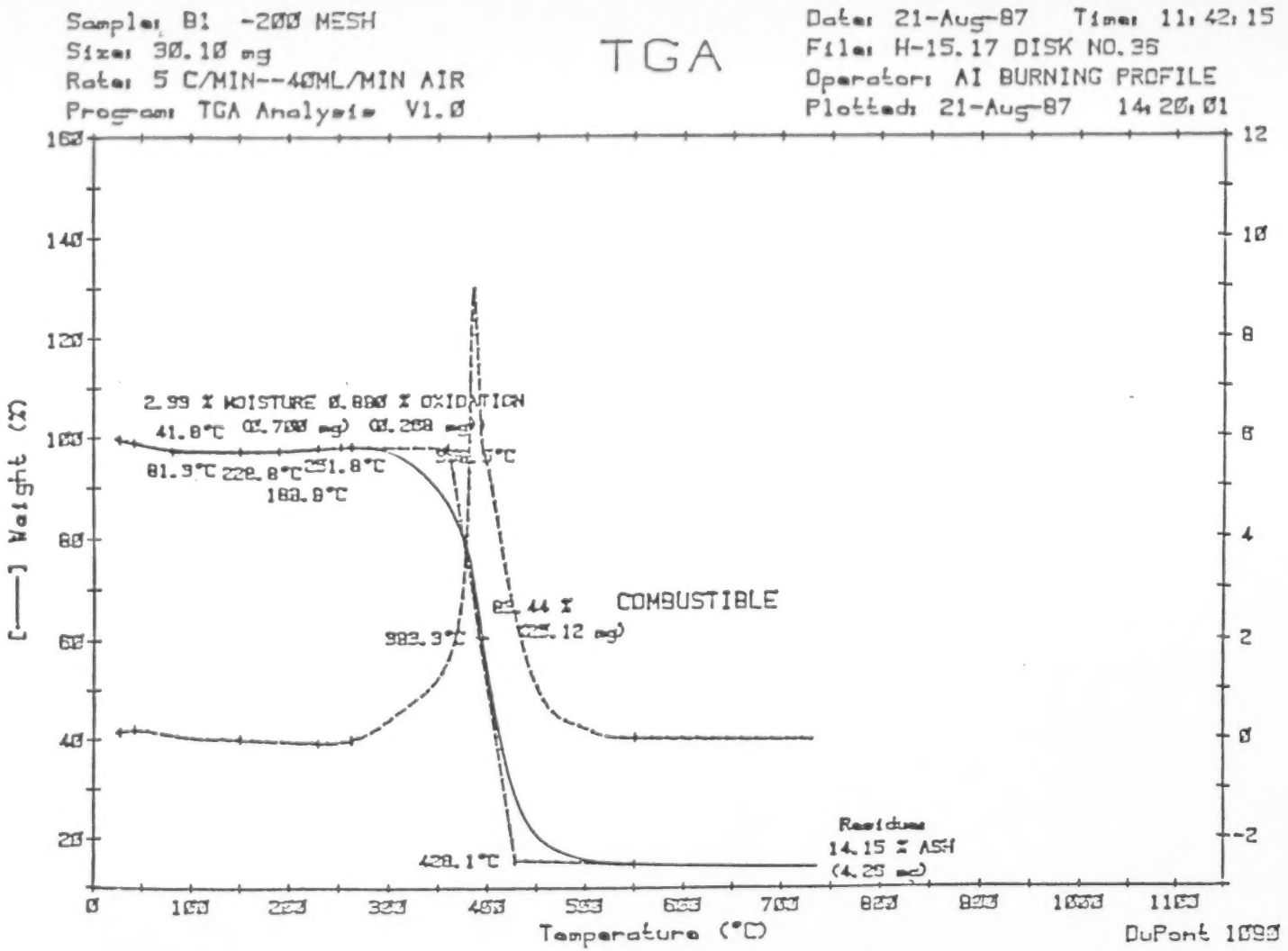


Figure 3.15 TGA Combustion Profile for Sample B1

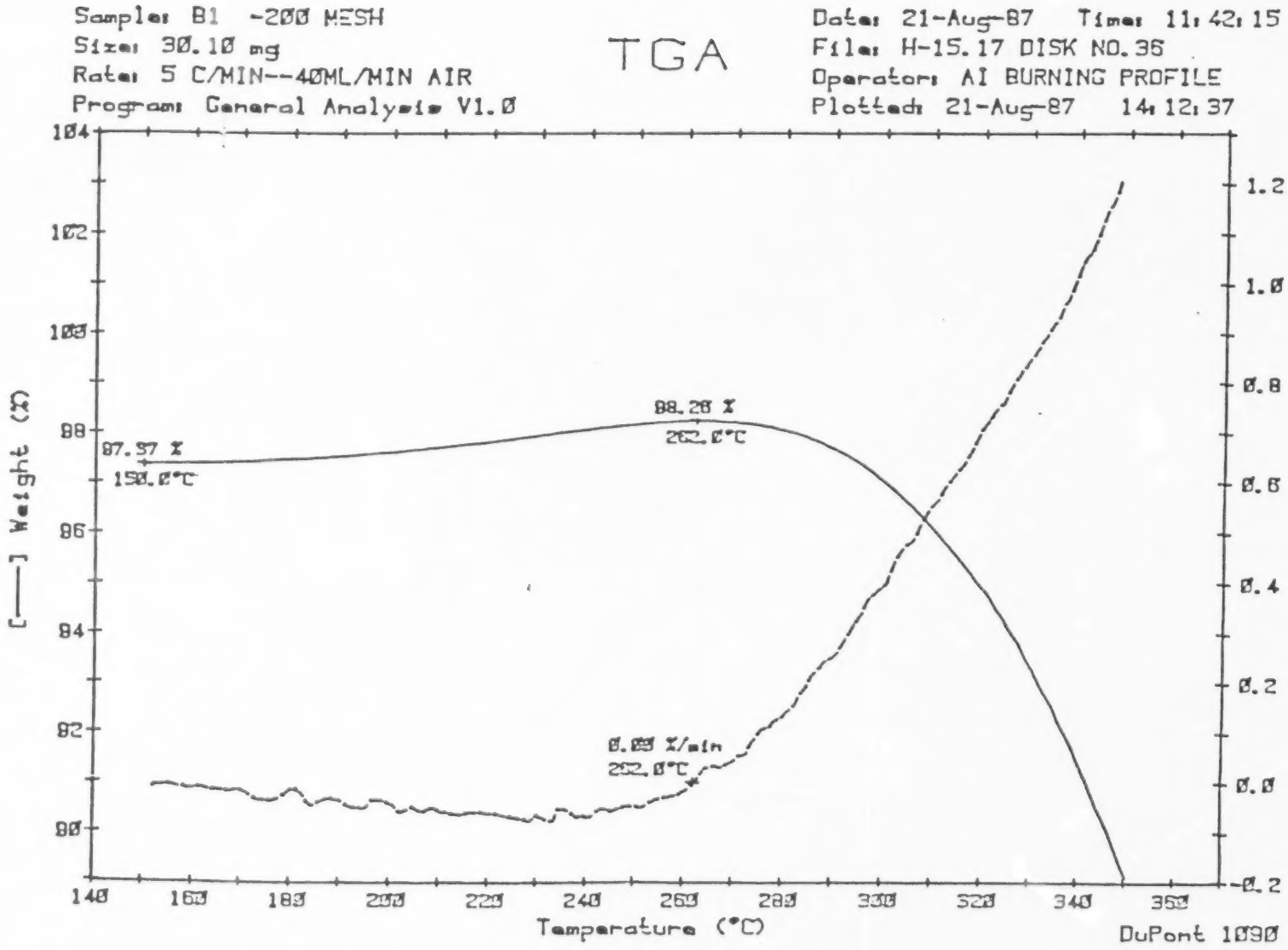


Figure 3.16 TGA Ignition Temperature for Sample B1

Sample: B1 -200 MESH
Size: 30.10 mg
Rate: 5 C/MIN--40ML/MIN AIR
Program: TGA Analysis V1.0

Date: 21-Aug-87 Time: 11:42:1
File: H-15.17 DISK NO.36
Operator: AI BURNING PROFILE
Plotted: 21-Aug-87 14:31:34

Transition	Onset [°C]	Inflection [°C]	Completion [°C]	Weight [mg]	Weight [%]
MOISTURE		41.8	81.3	0.70	2.33
OXIDATION	188.9	228.8	251.8	(0.27)	(0.88)
COMBUSTIBLE	358.5	383.3	428.1	25.12	83.44
ASH	Residue at 736.7 °C			4.26	14.15

Modified Sample Weight: 30.10 mg

Figure 3.17 TGA Combustion Profile Temperatures for Sample B1

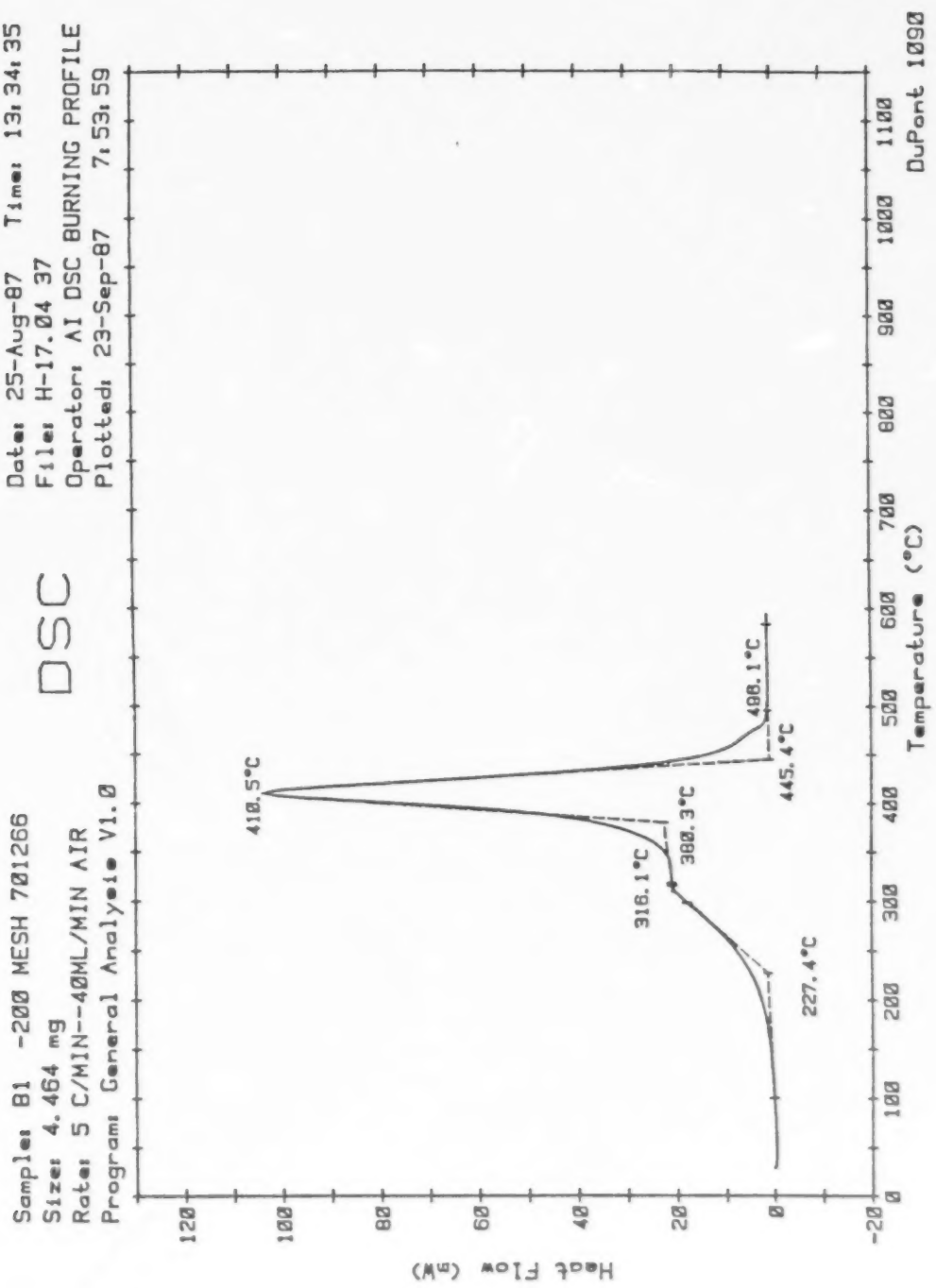
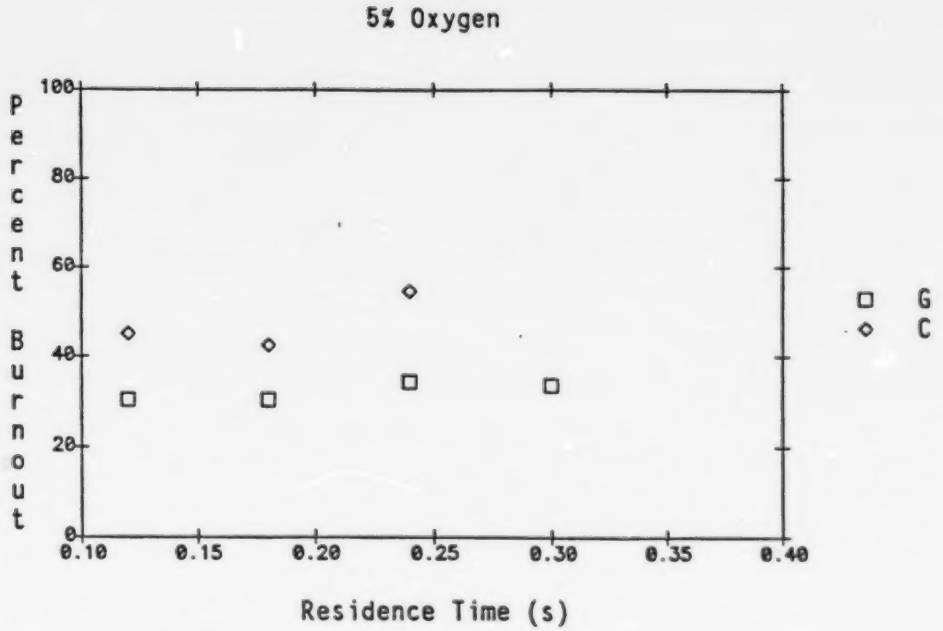


Figure 3.18 DSC Profile for Sample B1



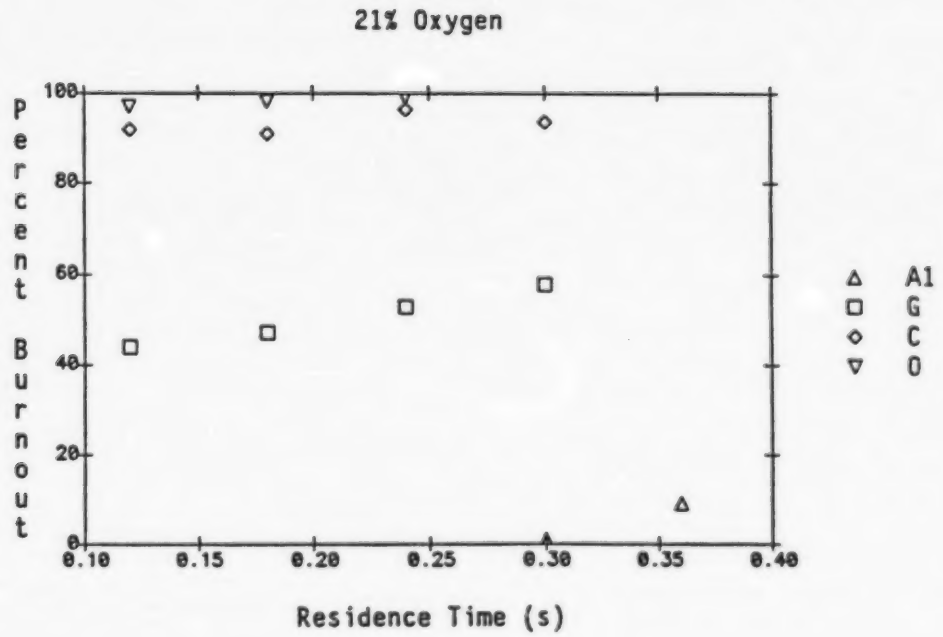


Figure 3.19 Relative Burnout of Anthracite and Coal Samples

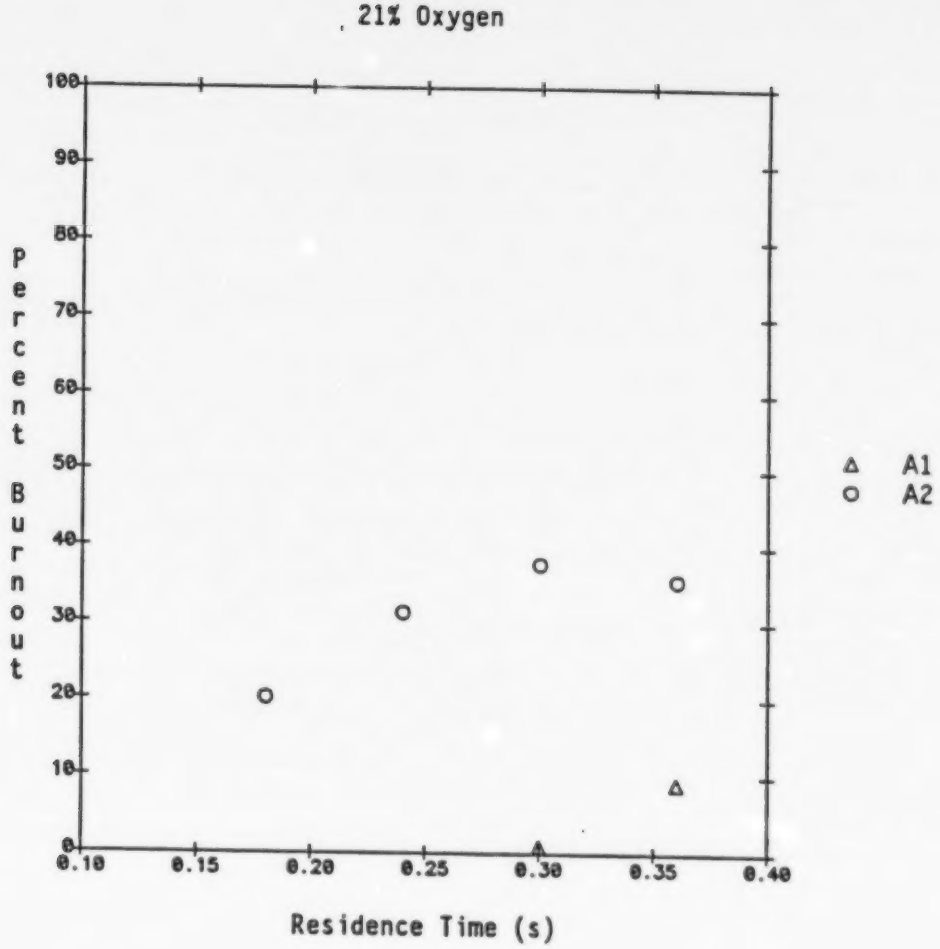
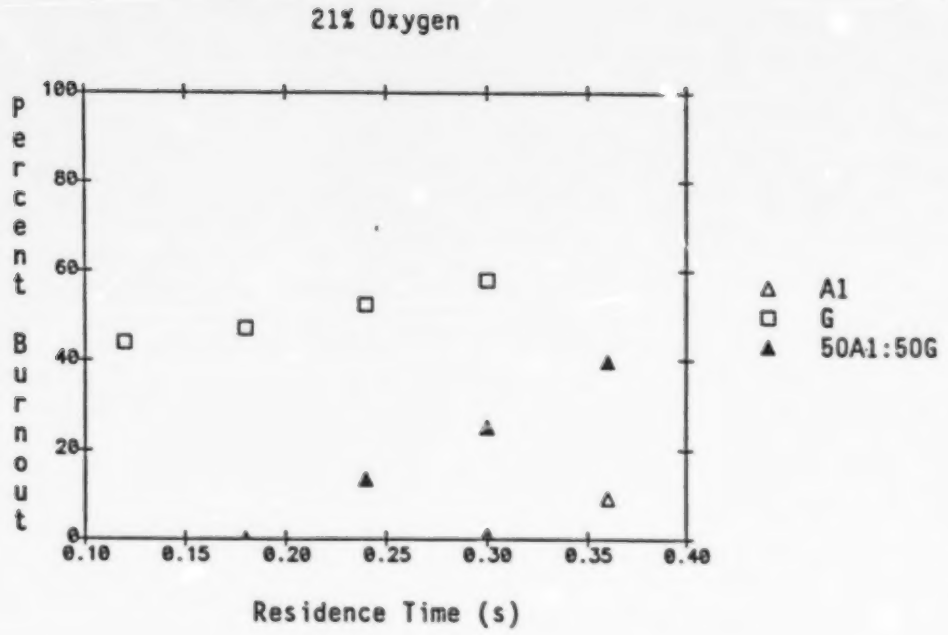


Figure 3.20 Relative Burnout of Micronized Anthracite



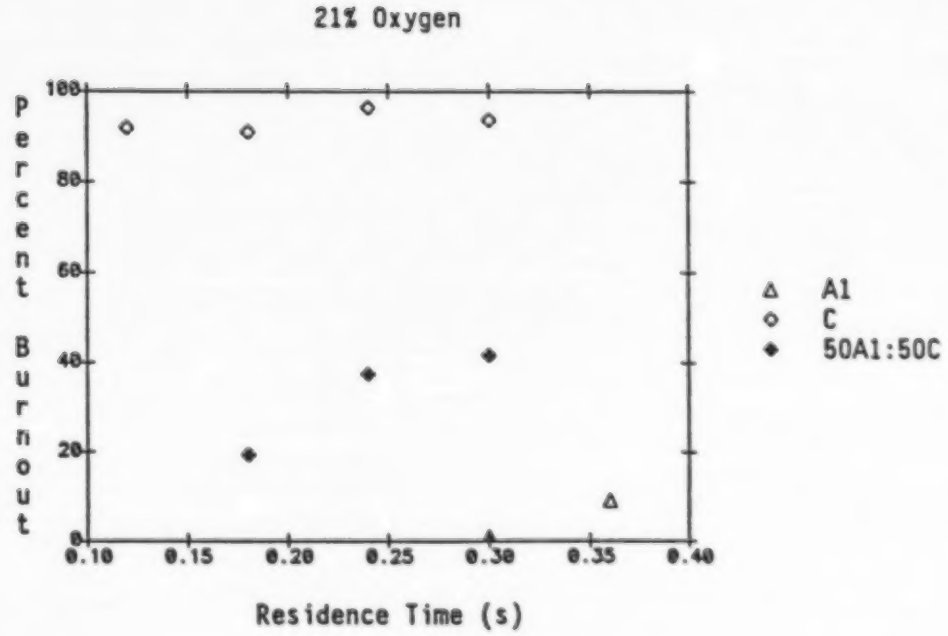
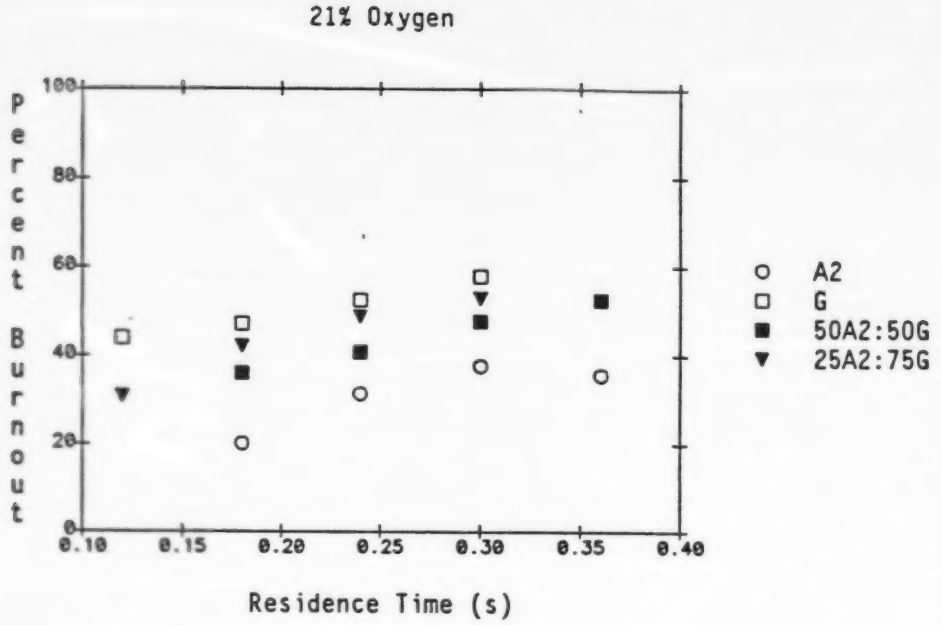


Figure 3.21 Relative Burnout of Blends of Anthracite and Thermal Coals



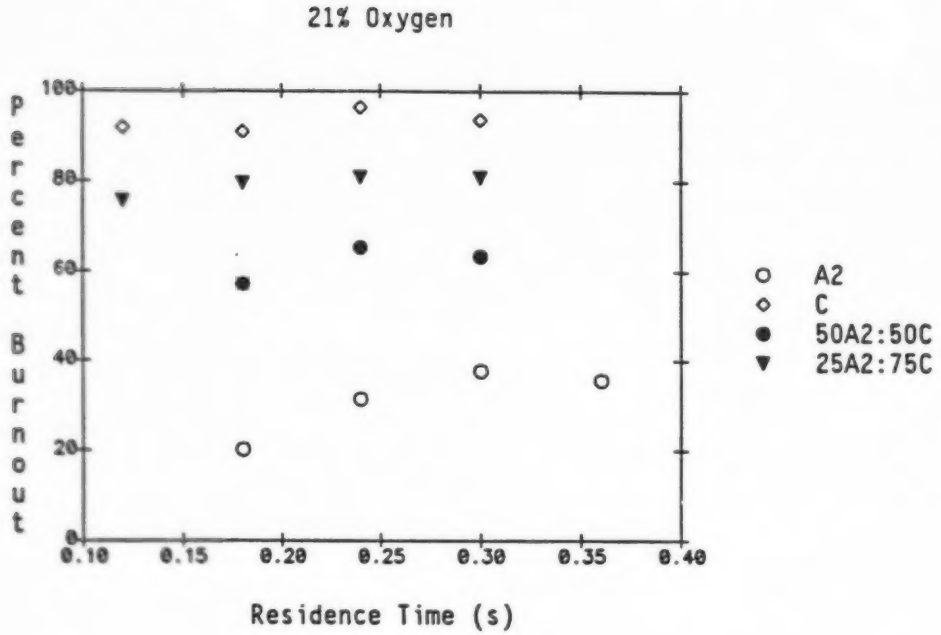


Figure 3.22 Relative Burnout of Blends of Micronized Anthracite and Thermal coals

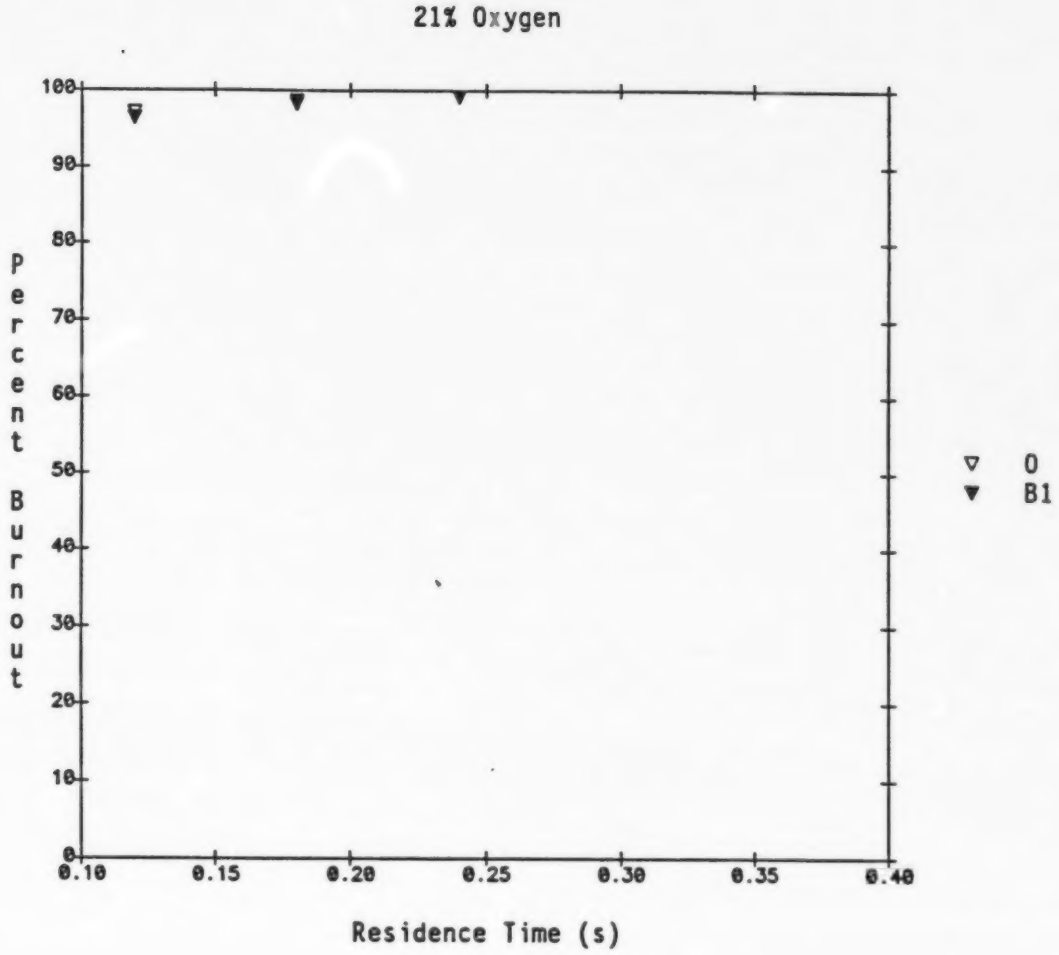


Figure 3.23 Relative Burnout of Beneficiated Product